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Autonomous Collaborative Unmanned Vehicles: Technological Drivers and Constraints

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(U) This report assesses the issues surrounding the eventual availability of autonomous collaborating unmanned vehicles. This report provides a high-level evaluation of the current state of the art of robotics in Canada and what technological barriers will need to be overcome to enable autonomous cooperating unmanned vehicles by the year 2025 for supporting the Department of National Defence (DND) missions.

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(U) Research and Development; Technology; Autonomous Intelligent Systems; Unmanned Autonomous Vehicles; Unmanned Platforms; Robotics; Artificial Intelligence; Vehicle Performance Optimization; Canadian Capabilities in Robotics; UAV; UGV; USV; UUV; UOV

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Autonomous Collaborative Unmanned Vehicles: Technological Drivers and Constraints

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EXECUTIVE SUMMARY

INTRODUCTION

Autonomous intelligent entities have been the focus of a substantial amount of research, both within Canada and internationally, over the last ten years. This report provides a high-level evaluation of the current state of the art of this technology in Canada. It also presents the technological barriers that must be overcome to enable autonomous cooperative unmanned vehicles to support Department of National Defence (DND) missions by the year 2025. These unmanned vehicles, or robots, would support the execution of dull, dirty and dangerous missions and will reduce the likelihood of military personnel being placed in harm's way.

When considering robots for service in 2025, one should consider their roles within the following battlespaces: space/orbital (UOV); air (UAV), ground (UGV); water surface (USF); undersea (UUV); cyber (UCV) and interbody (UIV). Each of these battlespaces share many common technology requirements; each battlespace also has unique enabling technology requirements.

Figure 1: Autonomous Control vs. Time presents an evolutionary view of autonomy within a UAV context:[1]

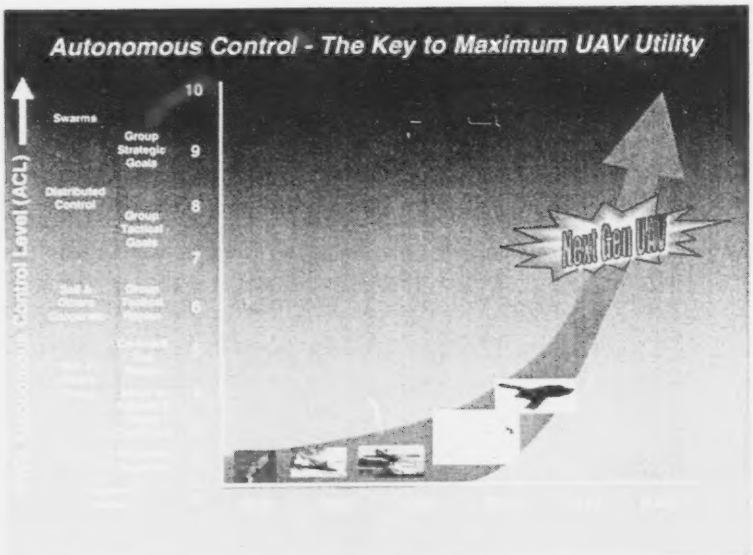

Figure 1: Autonomous Control vs. Time

This report provides a concise assessment of the capabilities and considerations required for autonomous unmanned vehicles in each of the defined battlespaces. This report is the

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[1] Applications, Concepts and Technologies for Future Tactical UAV's, RTO Lecture Series 224, pg 7-9, Feb 2003

EXECUTIVE SUMMARY

INTRODUCTION

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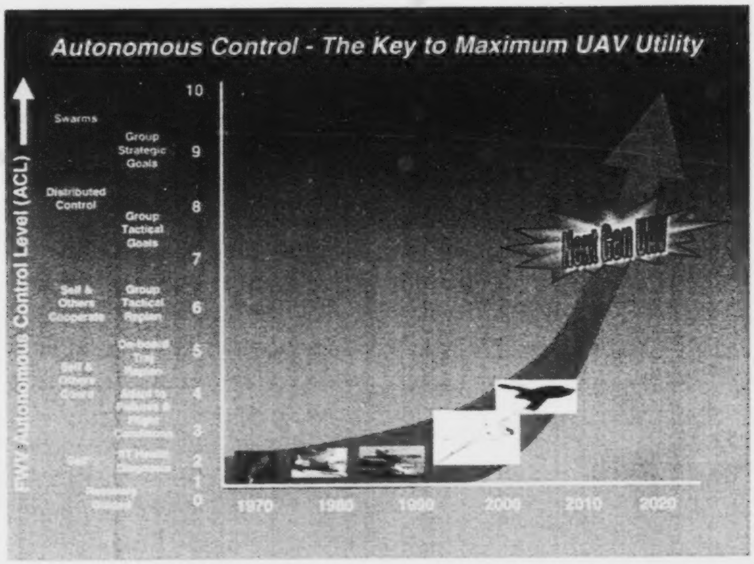

Figure 1: Autonomous Control vs. Time

This report provides a concise assessment of the capabilities and considerations required for autonomous unmanned vehicles in each of the defined battlespaces. This report is the baseline with which the evolution of these vehicles can be compared and tracked. These considerations take into account the following higher-level categories:

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[1] Applications, Concepts and Technologies for Future Tactical UAV's, RTO Lecture Series 224, pg 7-9, Feb 2003

- Deployment/Launch/Recovery
- Terrain/Medium/Environment
- Capability/Task/Weapons
- Navigation/Communications
- Robustness/Maintenance
- Force Integration
- Scale Effects

MISSIONS

Generally, the current belief is that UXVs can play mission roles as shown in Table 1 Missions and UXVs' Ability to Participate. These missions relate to Table 2: Assessment of Potential Missions for Criticality.

Table 1 Missions and UXVs' Ability to Participate[2]

	UAV	UGV	USV	UUV	UOV	Cyber
1. Broad Area Reconnaissance: This refers both to imaging broad areas as well as the ability to range over a large area on a single mission, while imaging only selected targets.	X	X	X	X	X	X
2. Denied Area Reconnaissance: Information collection in areas where permission to overfly/enter would be denied.	X	X	X	X	X	X
3. Tactical Surveillance/Reconnaissance: Persistent coverage of a specific target of interest, or the need to find out what is just over the next hill.	X	X			X	X
4. Moving Target Indicators for Surveillance/Battle Management: Air, Ground and Maritime MTI are growing in importance as a battle management tool as well as a cueing system for high-	X	X	X	X	X	X

---

[2] Unmanned Aerial Vehicles Roadmap 2002-2007, Office of the Secretary of Defense, pg 87 & 88

	UAV	UGV	USV	UUV	UOV	Cyber
resolution imagery.						
5. Intel Prep of the Battlefield: Pre-hostility information collection of an area where combat may occur.	X	X	X	X	X	X
6. Precision Guided Weapons Targeting: Specific sensor requirements for pointing and imaging accuracy to provide precise geo/network coordinates.	X				X	X
7. Urban/network Surveillance/Reconnaissance: Observation of targets in an urban environment.	X	X				X
8. Force Protection: Tasks include perimeter surveillance/defence, chem/bio agent detection, network and target identification.	X	X	X	X		X
9. Chemical/Biological Agent Detection and identification: Patrol an area searching for evidence of a chem/bio attack.	X	X	X	X		X
10. Battle Damage Assessment: Provide high-resolution imagery in a hostile environment.	X	X	X	X	X	X
11. Homeland Defense: Long dwelling surveillance with special sensors aimed at weapons of mass destruction or chem/bio.	X	X	X	X	X	X
12. Battlefield Simulation/Rehearsal: traverse the terrain to be used in an exercise and develop the digital maps to be used in the rehearsal.[3]	X	X	X	X	X	X
13. Oceanography: Mapping/survey of ocean floor			X	X		
14. Anti-Submarine Warfare	X		X	X		
15. Mine Clearing/counter measures		X	X	X		
16. Communications Hub or	X	X	X	X	X	X

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[3] Unmanned Aerial Vehicles Roadmap 2002-2007, Office of the Secretary of Defense, pg 87 & 88

	UAV	UGV	USV	UUV	UOV	Cyber
Navigation Aid						
17. Search and Rescue	X	X	X	X	X	X
18. Convoy Duty	X	X	X	X		X
19. Casualty Evacuation		X	X	X		
20. Electronic Warfare	X	X	X	X		X

Table 2: Assessment of Potential Missions for Criticality

		Criticality of Mission		
		Low	**Medium**	**High**
Frequency of Mission	**High**		1, 3, 11,13, 20	
	Medium	12,18	7,17	14,15
	Low	19	2, 9, 10	4, 5, 6, 8

CAPABILITY REQUIRMENTS AND TECHNOLOGY DEVELOPMENT

This general architecture developed by the US National Academy of Science can be seen in Figure 2: UXV Capability Requirements. This architecture is logically segmented into two portions, the first is the autonomous behaviour that provides the higher level capabilities of the vehicle; the second is the UXV platform which provides the underlying structural capabilities that allow the first portion to interact with the world.

The capability of the UXV to directly impact operational outcomes can be mapped into the UXV Technology Development Space. The technology development space defines the relevant dimensions associated with UXV deployment – and the impact thereof. In order to maximize the direct impact of a UXV on an overall operation, the following dimensions need to considered:

- Enabling technology development;

- Technology integration (the integration of the enabling technologies into a useful package);
- Mission complexity (the more complex the mission, the greater the direct impact on the overall operation).

Arguably, very simple missions, with loosely integrated enabling technologies, can make a significant impact on a given operation. However, historically, with some exceptions, the largest military impacts have been achieved with well-developed, tightly integrated technology and missions which required substantial planning/complexity.

The interaction of these three dimensions is shown in Figure 3: UXV Technology Development Space.

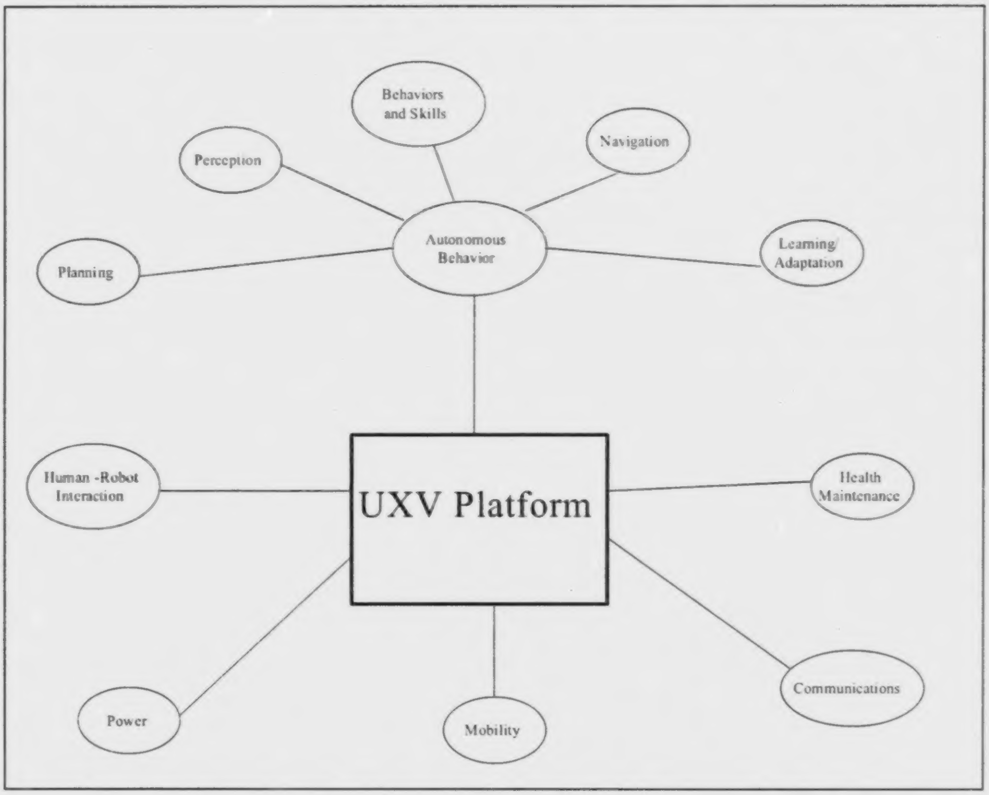
Behaviors and Skills
Perception
Navigation
Autonomous Behavior
Planning
Learning/ Adaptation
Human -Robot Interaction
UXV Platform
Health Maintenance
Power
Mobility
Communications

Figure 2: UXV Capability Requirements

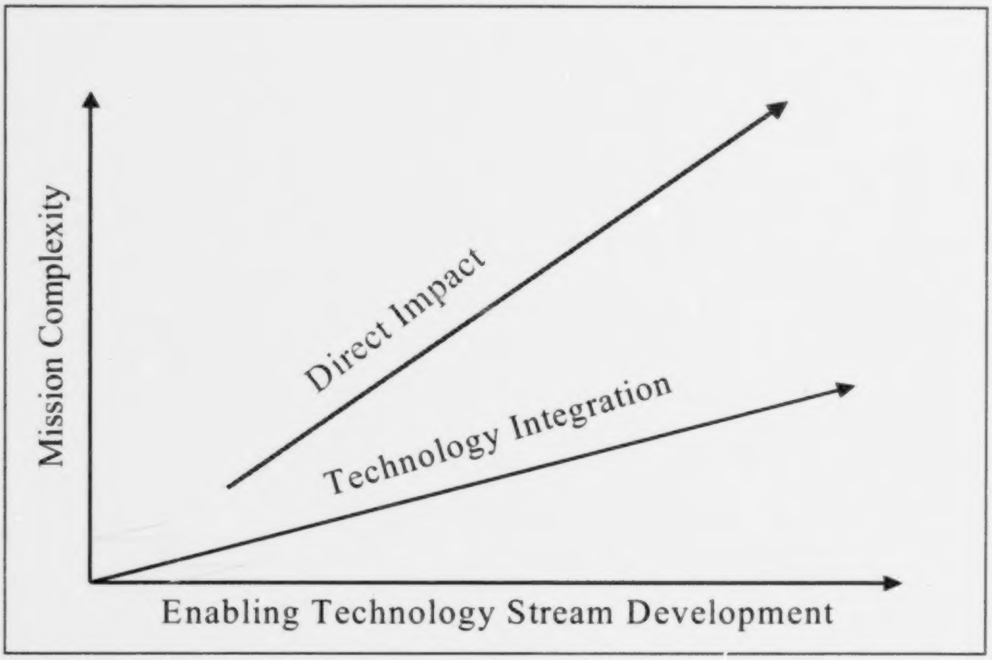

Figure 3: UXV Technology Development Space

ENABLING TECHNOLOGY STREAMS

The components of the general architecture that make up the autonomous behaviour and the UXV platform as well as technologies areas that will enable the emergence of new capabilities fall into the following *Enabling Technology Streams*:

- **Robotics, Dynamics and Mobility**
    - Propulsion Systems
- **Intelligent Software, Sensing and Navigation**
    - Planning, perception, behaviour and skills, learning and adaptation, health maintenance, human machine interactions
- **Control Systems**
- **Materials**
- **Communications**
- **Power/Energy Systems**

Fundamentally, these technology streams will require sophisticated integration. The development of the streams and associated integration efforts lead to more complex mission capabilities – and ultimately, increased direct impact on operational outcomes.

Table 3: Core Technology Trends provides a list of core technologies for autonomous vehicles in terms of present-day capabilities; it also lists the requirements for such technologies to support autonomous vehicles by 2020. *Note: relevance to the*

aforementioned Enabling Technology Stream(s) is indicated in bold for each Core Technology.

Table 3: Core Technology Trends[4]

Core Technologies	Today	2020
Computing Power SSI, LSI, VLSI, Parallel Processing, Optical Computing, Protein Based Computing **Relevant to: Intelligent Software, Sensing and Navigation**	MIPS	BIPS
Sensor Detection/Resolution Scanned/Staring Arrays, Electronically Steered Antenna (ESA), Ring Laser Gyro (RLG), Fiber Optic Gyro (FOG) **Relevant to: Intelligent Software, Sensing and Navigation**	5 Km 0.5 mrad	50 Km 0.001 mrad
Algorithmic/Symbolic Methods Classical state space, Soft Computing, Fuzzy logic/Neural Nets, AI, Genetic Methods, Behaviour-based Techniques **Relevant to: Intelligent Software, Sensing and Navigation**	Deterministic Multi loop system control	Adaptive Multi-dimensional Mission loop Optimization
Modeling and Simulation [Super Computing, CAD, 3D Visualization, Multi-media Agent Based Techniques **Relevant to: Robotics, Dynamics and Mobility; Intelligent Software, Sensing and Navigation; Control Systems**	High Fidelity Integrated System Constructs	Virtual Reality Environment
Communication/Information Distribution Internet Infrastructure, search Engines, Data/Info Extraction **Relevant to: Communications**	Massively High Integrated Systems Constructs	Network-Centric Multi-Media Information
Navigation Accuracy Autonomous Inertial Navigators, Satellite Navigation, Digital Terrain Mapping, 4-D Navigation **Relevant to: Intelligent Software, Sensing and Navigation**	100 m/h	1 – 10 m/h <1m.
Flight Path Trajectory Management Fly-by-Wire, Multi Variable Closed Control, Multi-Vehicle Distributed Cooperative Control, Formation Positioning **Relevant to: Control Systems**	Integrated Flight Mgmt with Human Operator Oversight	Missionized Configuration Tailoring
Vehicle Management Architecture Distributed processing, MEMS, Photonics, MIMo Instrumentation, Fault Tolerant/Reconfigurable Command Signaling, Health Monitoring-Diagnostics and Prognostics **Relevant to: Intelligent Software, Sensing and Navigation; Control Systems**	Automated Subsystem Control	Real-time Integrated Performance Optimization
Real Time On-Board Mission Functions Sensing, Digital Processing, Information Fusion, Artificial Intelligence, Knowledge-based Systems **Relevant to: Intelligent Software, Sensing and Navigation**	Integrated Mission System Functionality	Self Situation Assessment Autonomous Mission Management
Airframe Integration Sensor/Control Configured Vehicle, High Agility Blended Wing Body, Smart/Morphing Structures, Virtual Prototyping **Relevant to: Robotics, Dynamics, Mobility; Materials; Power/Energy Systems**	Human performance Limits	Missionized Configuration Tailoring

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[4] Applications, Concepts and Technologies for Future Tactical UAV's, RTO Lecture Series 224, pg 4-9 Feb 2003

As with most technologies, increasing the complexity of missions requires optimization of certain components (i.e., enabling technology streams). Generally, this results in an increased optimization of the integrated package (although sub-optimization can occur if there is an excessive amount of focus on a particular component or outcome).

PERFORMANCE OPTIMIZATION

Increasing Optimization can be measured in terms of improvements in the relevant performance metrics. These metrics include:

- **Vehicle Scale**
- **Range and Endurance**
- **Maintainability**
- **Availability**
- **Reliability**
- **Survivability**
- **Payload**
- **Detectability (Stealth)**
- **Cost**
- **Autonomy**

These metrics are discussed in further detail in Section 6 of this report.

DISRUPTIVE TECHNOLOGIES

Disruptive technologies are new or existing devices used in an innovative fashion that significantly alter established practices. Within a military context, disruptive technologies:

- Change the "business model" of the military or part thereof;
- Are evaluated on a different performance metric(s); and
- Can incubate in fringe commercial markets that are relevant to the military – or in fringe markets within the military itself.

In contrast, *sustaining technologies* foster improved product performance along an established trajectory. They also maintain an organization's business model. However, sustaining technologies often provide more features than customers need or want.[5] Regardless, the majority of the income derived from technological development is based on sustaining technologies.

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[5] Christensen, Clayton, *The Innovator's Dilemma*, HBS Press, 1997.

The potential for UXVs to become disruptive is very high. Clearly these technologies could significantly alter the military business model. Performance metrics may be different or the UXV may be substantially improved for a given metric (e.g., endurance). If a UXV is deemed expendable, the risk calculation associated with the mission will change. If human operators are not on-board the vehicle, size constraints and mission constraints are altered.

Accordingly, UXVs will likely have a truly disruptive effect on the military and on the incumbent players within the industrial complex which supports the military. This has national and international economic implications.

RESEARCH GAPS

The report provides data on *Research Universities and Enabling Technology Areas.* The areas of expertise for each of the major universities in Canada, which relate to technologies of interest to an Autonomous Vehicles program, have been identified. This data is an amalgamation of NSERC-funded grants and scholarships with published information on each university Web site.

Data presented in this report indicates that intelligent software and sensing research is well-represented at Canadian universities. However, the Defence community will need to oversee a portion of this research so that it meets their currently undefined needs. Without this oversight and involvement, it is unlikely that the Canadian Research community will work on military-specific technology.

Data presented in this report also indicates the gaps in Canadian university research and development for the UXV enabling technology streams. These are:

- Robotics
- Mobility
- Navigation

Additional areas which are somewhat lean are:

- Communications
- Power

If UXVs are going to become part of the Canadian industrial landscape, these gaps will need to be addressed – through direct efforts, national or international partnering. Such partnering may occur through the Canadian Space Agency (CSA), National Sciences and Engineering Research Council of Canada (NSERC), PRECARN Associates Inc. and/or the Institute for Robotics and Intelligent Systems (IRIS). The CSA has demonstrated that a focussed effort on a particular mission can galvanize university research efforts. Their approach to basic technology research is as follows.

CSA conducted research in basic technology for the Canadarm and the Mobile Servicing Station (MSS). To achieve the desired outcomes, they:

- Identified core technology areas where the expertise in Canada was lacking, in order to develop the systems; and
- Invited university-industry teams to prepare proposals for research projects in the identified technology areas.

The research projects had three phases of funding. At the conclusion of each phase, the university-industry teams that had won the earlier phase competed with each other for funding in the next phase. The phases were structured as follows:

- The first phase had a maximum value of $100,000. Typically, this phase involved a technology investigation, possibly some prototyping, and the development of a phase 2 project plan.
- The second phase was funded to a maximum of $1,000,000 (typically one-in-three first-phase teams were awarded phase 2 projects). Phase 2 was a technology demonstration project and required the team to provide some level of matching funds and to show a commercialization path for the effort. As part of the evaluation for contract award, the potential that the results of the effort would lead to a commercial product for one or more members of the team was assessed; the commitment by the team to commercialize the effort was also considered.
- The third phase was only funded if the technology was to be incorporated into the Canadarm or the MSS.

This type of research mechanism may offer attractive benefits to DND and provide a strong research pipeline for autonomous UXV deployment by 2025. In addition, utilization of the existing agreements between DND and NSERC, PRECARN/IRIS, NRC, etc. to partially fund their programs, would ensure research efforts are funded by these groups that will support the goals of DND.

Table 4: Summary of Enabling Technology and Research (2001-02)

Enabling Technology	**Canadian Research Effort** *# of Grants Ave. $/Grant*	**Highest Intensity of Effort (University Locations)**	**$ Currently being Expended**
Robotics, Dynamics and Mobility	29 $32k/grant	Laval, École Poly, Carleton, Queen's, Guelph, Ottawa, Waterloo	$936k
Intelligent S/W, Sensing and Navigation	108 $29k/grant	Toronto, McGill, Alberta, Ottawa, Windsor, UBC	$3,107k
Control Systems	32 $41k/grant	UBC, Western	$1,320k
Materials	12 $35k/grant	McGill, Sherbrooke, Alberta, Laval, Queen's, UBC, Manitoba, Ottawa, Waterloo	$415k
Communications (see note below)	2 $29k/grant	Simon Fraser, Alberta	$58k
Power/Energy Systems	7 $39k/grant	Concordia, Dalhousie, McGill, Toronto	$274k

Note: Communications funding was heavily influenced by private-sector activity.

Table 5: Minimum Level of Effort to Realize a Fully Autonomous Vehicle

Enabling Technology	**Focus of Effort Required to Advance Existing Technology to Deployment Stage**
Robotics, Dynamics and Mobility	**UOV:** Well-established; incremental level of effort required **UAV:** Well-established; incremental level of effort required **UGV:** Significant work required on wheels, tracks and or legs to overcome obstacles and allow navigation on steep inclines or declines **USV:** Well-established; incremental level of effort required **UUV:** Well-established; incremental level of effort required **UCV:** Well-established; incremental level of effort required However, optical and wireless research is clearly required (new highways).
Intelligent S/W	**All Battlespaces:** Significant work to add behavioural adaptation and learning
Sensing	**UOV:** Well-established; incremental level of effort required **UAV:** Object recognition when moving, target and threat recognition required **UGV:** As per UAV plus obstacle recognition, path optimization/viability

Enabling Technology	**Focus of Effort Required to Advance Existing Technology to Deployment Stage**
	USV: Object recognition when moving, target and threat recognition required **UUV:** Well-established, incremental level of effort required **UCV:** Network, Server, spoofing, target and threat recognition required
Navigation	**UOV:** Significant issues surrounding precise location knowledge **UAV:** Well-established; incremental level of effort required **UGV:** Significant issues surrounding: holes in GPS coverage, obstacle avoidance, cluttered environments **USV:** Well-established; incremental level of effort required **UUV:** Well-established; incremental level of effort required **UCV**: Significant issues beginning with mapping the Internet; Means to navigate through firewalls and other security devices; Finding well-hidden targets
Control Systems	**UOV:** Well-established; incremental level of effort required **UAV:** Well-established; incremental level of effort required **UGV:** Issues surrounding mobility, balance, etc.; moderate effort required **USV:** Well-established; incremental level of effort required **UUV:** Well-established; incremental level of effort required **UCV:** Significant effort required
Materials	All battlespaces – significant effort in nanotechnology required and underway
Communications (see note below)	**UOV:** Well-established; incremental level of effort required **UAV:** Well-established; incremental level of effort required **UGV:** Moderate research into solutions for communications disruptions due to cluttered environment **USV:** Well-established; incremental level of effort required **UUV:** Well-established; incremental level of effort required **UCV:** Moderate effort to secure packet transmission back to base
Power/Energy Systems	**UOV:** Well-established; incremental level of effort required **UAV:** Well-established; incremental level of effort required; however, for small-scale, significant work is required **UGV:** Well-established; incremental level of effort required; however, for small-scale, significant work is required **USV:** Well-established; incremental level of effort required; however, for small-scale, significant work is required **UUV:** Well-established; incremental level of effort required; however, for small-scale, significant work is required **UCV:** Dependent on network power

Commercialization

The enabling technology streams clearly are vital if UXVs are to be deployed in the future. Commercialization of the output from these streams will also be required to effectively advance the technology. How does one determine the proximity to commercialization of a given technology stream development? This is a difficult task. At a minimum, there are three technology development paths towards UXV deployment:

- Direct-focus development;
- Modification of platforms developed by others;
- Integration of commercialized and non-commercialized sub-components.

The first path is essentially a brute-force approach. The project leaders need to be empowered to develop and integrate whatever they need to achieve their desired goals. There are several examples of this in the history of technology. A dramatic case of this is the American Apollo program. Neither the science nor the technology were in place to go to the moon in 1961. The infrastructure did not even exist. But a goal was set to land men on the moon prior to the end of the decade – and it was achieved. The cost, in today's dollars, was in the order of US$300 billion.

The second approach is simply a "buy and adjust" exercise. This is perhaps the easiest approach from a national effort viewpoint. However, it does little to develop national capabilities and the technology may not suit precise Canadian requirements.

The last approach has the hallmarks of a disruptive technology development process – although the other methods have disruptive potential also. This involves using existing technology components, putting them together in a unique way – and deploying them in a unique manner also. It is an integration and unique-use exercise and is probably a medium-cost solution.

To truly assess how close a technology is for DND's requirements, an assessment based upon the anticipated missions and battlespaces for the UXV will be required. Consideration of missions and battlespaces will have a dramatic impact on the commercialization path. Carrying out such an assessment is beyond the scope of this report.

This discussion underscores that a commercialization path for UXVs (particularly military-focussed) is very difficult to map. Enabling technologies may be developed solely for the UXV, they may be commercialized off-the-shelf components with a clear value proposition, or they may be some sub-system of a larger piece (middleware). Regardless, development within a given enabling technology stream can be monitored – and this provides an indication as to what options are available for UXV deployment.

1 Introduction

Autonomous intelligent entities have been the focus of a substantial amount of research, both within Canada and internationally, over the last ten years. The Canadian Space Agency, the Natural Sciences and Engineering Research Council (NSERC), PRECARN/IRIS and other groups have funded well in excess of $50 million in research of enabling technologies (more details regarding these projects are in Section 7.1). US efforts have been in excess of 10 times this $50 million figure.[6,7] The value of such autonomous entities to undertake certain missions (military or commercial) is being actively evaluated by the US Defense Department (for example: UGV/S Joint program office, Air Force Research Laboratory, Program Management Office for EOD navy, US Army TACOM Research Development and Engineering Center Product Manager – Physical Security Equipment, AMCOM Research Development and Engineering Center, Defense Advanced Research Projects Agency, Army Research Laboratory), various coalition partners and countries such as Israel in terms of reduced risk to personnel, increased effectiveness and favourable economics as can be seen from the documents in the bibliography. Various autonomous systems are becoming commercially available as toys or to perform specific tasks for humans as discussed in Section 3.3, Emergence of Single Mission Robots into Everyday Life.

This report assesses the issues surrounding the eventual availability of autonomous collaborating unmanned vehicles. Such vehicles are a form of autonomous robot. Other forms of autonomous robots include stationary multi-arm manufacturing robots, medical robots, etc. The physical form of such a vehicle includes: winged UAV's like today's systems but with much more on-board intelligence on how to execute its assigned mission; trucks and motorcycles based around the current efforts in tethered vehicles; small boats or submarines. Other less commonly envisioned forms for these robots could be small hockey-puck-sized flying Electronic Warfare platforms (such as Air Mobility Ground Security and Surveillance Systems [AMGSSS] by SPAWAR), swarms of bee-size autonomous flying video cameras, humanoid sentries, swimming cameras, etc.

This report provides a high-level evaluation of the current state of the art of robotics in Canada and what technological barriers will need to be overcome to enable autonomous cooperating unmanned vehicles by the year 2025 for supporting the Department of National Defence (DND) missions. These unmanned vehicles, or robots, would support the execution of dull, dirty and dangerous missions and will reduce the likelihood of military personnel being placed in harm's way.

When considering robots for service in 2025, it is important to consider their performing a role in the following battlespaces: space, air, ground, water surface, submerged, cyber

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[6] Unmanned Aerial Vehicles Roadmap 2002-2007, Office of the Secretary of Defense, pg 20

[7] The Navy Unmanned Undersea Vehicle (UUV) Master Plan April 20, 2000, pg. ES-3

and interbody. Each of these battlespaces share many common technology requirements while each has unique enabling technology requirements.

The first five battlespaces could have robots that are significantly bigger than human scale, the same size as humans, and smaller than humans. Again the size will have an impact on the necessary enabling technologies. For example, the flight dynamics of a flying robot the size of a penny will be different from that of a UAV with a six-foot wingspan. A penny-sized UAV will also require micro and nano technology to build the instrumentation and propulsion systems.

The sixth battlespace will have virtual robots, agents or computer programs (cyberbots) that protect and attack computer installations connected via Internet or new wireless protocols. The last battlespace is inside the body of the service personnel and would facilitate cell repair, response to toxins, injection of stimulants and other chemicals into the blood stream as the nanobot deems necessary for the proper functioning of the human.

To some people, the autonomous robotic entity may sound like a piece of science fiction. It is worthwhile to note the following:

> "There is no inevitable tomorrow. All that we know for sure is the almost unstoppable acceleration of science and technology, and the drastic impact it will have upon humanity and our world."[8]

In reality, when considering how science and technology might influence tomorrow, it is necessary to realize that significantly more than 50% of all scientists, mathematicians and engineers that have ever lived on this planet are alive **today**.

1.1 Objectives and Scope

The objectives of this report are twofold:

1. To provide the reader with a technology map that represents UXV enabling technologies, which will include gaps and the intermediate steps required in reaching the end state. The development and integration of these technologies could lead to the deployment of autonomous robotic entities by the year 2025.

2. To establish a baseline for those enabling technologies that is considered to be relevant to the successful deployment of UXVs. The baseline would identify:

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[8] The Spike, How our lives are being transformed by rapidly advancing technology, Damien Broderick, 2001

a) Those technologies that would be required to make the concept a reality;
b) The current status of research in Canada as a minimum, and North America, if possible;
c) The gap between the level of technological development required for deployment and the current status of the technology;
d) An estimate of how close the enabling technology is to commercialization;
e) Where the current activity in each field is most intense; and
f) The level of effort that is being expended in each field.

The scope of this project is limited to technological considerations. Policy implications will not be included.

1.2 Definitions

A comprehensive glossary is appended to this report. However, certain key definitions are presented here in the interests of clarity and document flow.

Artificial Intelligence: The programming and ability of a robot to perform functions that are normally associated with human intelligence, such as reasoning, planning, problem solving, pattern, recognition, perception, cognition, understanding, learning, speech recognition and creative response.

Autonomous: A mode of control of a UXV wherein the UXV is self-sufficient. The UXV is given its global mission by the human, having been programmed to learn from and respond to its environment, and operates without further human interventions.

Robot: A machine or device that works automatically or operates by remote control.

Robotics: The study and techniques involved in designing, building and using robots.

Swarms: The use of multiple UXVs all active or working in a defined area carrying out the same mission. The UXVs can be working in a coordinated or uncoordinated fashion.

Telepresence: The capability of a UXV to provide the human operator, using video feedback and or other cues, the continuous direct controls of the actions of the UXV.

Unmanned Airborne Vehicle (UAV): A powered, mobile, airborne conveyance that does not have a human aboard; can be operated in one or more modes of control (autonomous, semi-autonomous, teleoperation, remote control); can be expandable or recoverable; and can have lethal or non-lethal mission modules.

Unmanned Cyber Vehicle (UCV): UCVs are also known as Autonomous Agents and can be defined as "computational systems that inhabit some complex dynamic environment, sense and act autonomously in this environment, and by doing so realize a set of goals or tasks for which they are designed." [fromMaes, Pattie (1995), "Artificial

Life Meets Entertainment: Life like Autonomous Agents," *Communications of the ACM*, 38, 11, 108-114]

Unmanned Ground Vehicle (UGV): A powered, mobile, ground conveyance that does not have a human aboard; can be operated in one or more modes of control (autonomous, semi-autonomous, teleoperation, remote control); can be expandable or recoverable; and can have lethal or non-lethal mission modules.

Unmanned Orbital Vehicle (UOV): A powered, mobile, space conveyance that does not have a human aboard; can be operated in one or more modes of control (autonomous, semi-autonomous, teleoperation, remote control); can be expandable or recoverable; and can have lethal or non-lethal mission modules.

Unmanned Surface Vehicle (USV): A powered, mobile, water surface conveyance that does not have a human aboard; can be operated in one or more modes of control (autonomous, semi-autonomous, teleoperation, remote control); can be expandable or recoverable; and can have lethal or non-lethal mission modules.

Unmanned Underwater Vehicle (UUV): A powered, mobile, underwater conveyance that does not have a human aboard; can be operated in one or more modes of control (autonomous, semi-autonomous, teleoperation, remote control); can be expandable or recoverable; and can have lethal or non-lethal mission modules.

Unmanned Systems: A grouping of military systems, the common characteristic is that no human operator is aboard. May be mobile or stationary. Includes categories of unmanned ground vehicles (UGV), unmanned aerial vehicles (UAV), unmanned underwater vehicles (UUV), unmanned munitions (UM) and unattended ground sensors (UGS). Missiles, rockets and their sub-munitions, and artillery are not considered unmanned systems.

UXV: the class of unmanned systems representing the unmanned vehicles.

2 The Battlespaces and Robots

This section presents a high-level assessment of the capabilities and considerations required for autonomous unmanned vehicles in each of the defined battlespaces. These considerations take into account the following higher-level categories:

- Deployment/Launch/Recovery
- Terrain/Medium/Environment
- Capability/Task/Weapons
- Navigation/Communications
- Robustness/Maintenance
- Force Integration
- Scale Effects

Systems that will operate in future operations will need to be robust and multi-mission capable. These systems will need to work together with an ability to swap components to enable battlefield corrections and repair using parts salvaged from other robots. They will also need to display autonomous mobility to traverse from point A to point B and may need to display the tactical behaviours of a warfighter in order to survive in a dangerous situation. These systems will incorporate various replaceable manipulators and sensors while enabling the movement of smaller robots in a marsupial behaviour. Other behaviours these robots may need to exhibit are:

"Massing" – The ability to come together as a formation to overwhelm defenses and minimize losses;

"Rolexing" – The ability to adjust mission timing on the move to compensate for inevitable changes to plans and still make the time-on-target;

Situational Awareness (SA) – "expanding the soda-straw (narrow) field of view used by current UXVs that negatively affects their ability to provide broad SA for themselves, much less for others in a formation."[9]

Robots (sometimes called Mobile Sensors) are likely to play an increasingly important role in conventional and special operations warfare. These systems will be used to go into places where they could not go using conventional methods. These platforms will crawl, swim, fly or traverse space in other modes of mobility. Mobile sensors could be used to support the detection of chemical, biological or nuclear components, enabling safe handling or disposal. They will need to perform their missions in all weather conditions and should be recoverable or expendable. They will be used to ensure that areas are safe for humans to traverse, and identify threats that need to be cleared. They will play a large role in over-the-hill reconnaissance, electronic eavesdropping, EW jamming and psychological operations. Anti-tampering, anti-handling or destruction mechanism will evolve to help prevent reverse engineering of the systems or prevent captured/recovered systems from being used on friendly forces.

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[9] Brig Gen Daniel P. Leaf, Commander of the USAF Air Expeditionary Wing at Aviano, Italy, during operations in Kosovo.

In addition, for UXVs to participate in combat missions, the following challenges will need to be overcome:

1. " Rules of Engagement considerations that may require the intervention of a human;
2. The prosecution of advanced Integration Air Defense Systems (IADS) and time-critical targets through as yet unperfected Automatic Targeting and Engagement Process;
3. The integration, interoperability and information assurance required to support mixed manned/unmanned force operations;
4. Secure, robust communications capability, advanced cognitive decision aids and mission planning; and
5. Adaptive autonomous operations and coordinated multi-vehicle operation."[10]

Generally, the current belief is that UXVs can also play mission roles as outlined in Table 6. The roles have been categorized into a grid showing their frequency of mission versus their criticality in Table 7: Assessment of Potential Missions for Criticality.

Table 6: Missions and UXVs' Ability to Participate[11]

	UAV	UGV	USV	UUV	UOV	Cyber
1. "Broad Area Reconnaissance: This refers both to imaging broad areas as well as the ability to range over a large area on a single mission, while imaging only selected targets.	X	X	X	X	X	X
2. Denied Area Reconnaissance: Information collection in areas where permission to overfly/enter would be denied.	X	X	X	X	X	X
3. Tactical Surveillance/Reconnaissance: Persistent coverage of a specific target of interest, or the need to find out what is just over the next hill.	X	X			X	X
4. Moving Target Indicators	X	X	X	X	X	X

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[10] Unmanned Aerial Vehicles Roadmap 2002-2007, Office of the Secretary of Defense, pg 69

[11] Unmanned Aerial Vehicles Roadmap 2002-2007, Office of the Secretary of Defense, pg 87 & 88

	UAV	UGV	USV	UUV	UOV	Cyber
for Surveillance/Battle Management: Air, Ground and Maritime MTI are growing in importance as a battle management tool as well as a cueing system for high-resolution imagery.						
5. Intel Prep of the Battlefield: Pre-hostility information collection of an area where combat may occur.	X	X	X	X	X	X
6. Precision Guided Weapons Targeting: Specific sensor requirements for pointing and imaging accuracy to provide precise geo/network coordinates.	X				X	X
7. Urban/network Surveillance/Reconnaissance: Observation of targets in an urban environment.	X	X				X
8. Force Protection: Tasks include perimeter surveillance/defence, chem/bio agent detection, network and target identification.	X	X	X	X		X
9. Chemical/Biological Agent Detection and identification: Patrol an area searching for evidence of a chem/bio attack.	X	X	X	X		X
10. Battle Damage Assessment: Provide high-resolution imagery in a hostile environment.	X	X	X	X	X	X
11. Homeland Defense: Long dwelling surveillance with special sensors aimed at weapons of mass destruction or chem/bio.	X	X	X	X	X	X
12. Battlefield Simulation/Rehearsal: traverse the terrain to be used in an exercise and develop the digital maps to be used in the rehearsal."[12]	X	X	X	X	X	X

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[12] Unmanned Aerial Vehicles Roadmap 2002-2007, Office of the Secretary of Defense, pg 87 & 88

	UAV	UGV	USV	UUV	UOV	Cyber
13. Oceanography: Mapping/survey of ocean floor			X	X		
14. Anti-Submarine Warfare	X		X	X		
15. Mine Clearing/Counter measures		X	X	X		
16. Communications Hub or Navigation Aid	X	X	X	X	X	X
17. Search and Rescue	X	X	X	X	X	X
18. Convoy Duty	X	X	X	X		X
19. Casualty Evacuation		X	X	X		
20. Electronic Warfare	X	X	X	X		X

Table 7: Assessment of Potential Missions for Criticality

		Criticality of Mission		
		Low	**Medium**	**High**
Frequency of Mission	**High**		1, 3, 11,13, 20	
	Medium	12,18	7,17	14,15
	Low	19	2, 9, 10	4, 5, 6, 8

These robots will have a potential role in all of the arenas that Canada could find itself involved in over the next 25 years. These arenas are space, air, ground, marine, undersea cyber and interbody. The following sections are a very preliminary examination of these arenas and the technological issues involved in fielding robots into these arenas.

2.1 Space

Satellites represent the first sensors in space and for a long time have played a significant role in war by providing surveillance and communications support. New concepts for toaster-size satellites that carry specific sensor equipment and can be launched quickly and cheaply will open up the ability of various groups to launch their own "eye in the sky" or beyond line-of-sight communications switching devices. Several California universities have yearly competitions for their students to develop prototype miniature satellites. Potential concepts for use include being able to launch and recover satellite hunters, quick launch communications switches and new sensor payloads to support operation in a new theater. Re-enterable vehicles could be used for ultra-high observation of areas where normal entry would be forbidden and where manned over-flights would be too risky. Systems that could exit the earth's atmosphere use existing or new means for propulsion to move to specific areas would enhance the ability to observe activities. Of even greater interest would be a system with the ability to fly to specific areas so that there was no requirement to wait for the window of opportunity, a window that the observed can compute and prepare for. The task of developing autonomous robotic systems for space ops are hampered by the following issues:

Deployment/Launch/Propulsion/Recovery

- If re-entry is required, there are issues such as friction, loss of control, etc.
- Leave in space in a sleep mode – this has many issues surrounding the autonomous control of the vehicle during the sleep period such as station keeping, protection from meteor showers, power maintenance and control
- Launch cost and awkward process (rockets)
- Require significant quantities of propellant to operate or rely on new means of mobility (cosmic sails)

Terrain/Medium/Environment

- No 3D constraints
- Harsh environment
- Solar flares and meteor showers twice a year
- Lack of oxygen for lift, drag and other forces used in dynamic control of vehicle

Capability/Task/Weapons

- Limited roles due to difficulties in switching weapons or sensors, performing maintenance, satellite repair, etc.
- Hard to change or swap with new weapons

Navigation/Communications

- Costly motion/navigation – dedicated staff to monitor and control orbit/health
- Lack of available geosynchronous orbit slots suggest such robots will need to be in non-geosynchronous orbits for long-term location or they piggyback on existing satellites
- Communications tend to be broad-band, limited switching and network intelligence

Robustness/Maintenance

- Impact of space debris
- Materials
- Redundancy and re-routable circuits required

Force Integration

- Eye-in-the-sky
- Known position since orbits can be computed

Scale effects

- Large-scale has a significant impact on launch costs
- Small-scale results in payload sub-optimization

2.2 Air

Unmanned vehicles have the potential to contribute in many roles. Systems such as Global Hawk provide high-altitude surveillance, and in principle, weapon delivery. Smaller systems provide local surveillance, beyond line-of-sight communications and weapon targeting. Smaller airborne devices provide the unit or the individual with over-the-hill reconnaissance; swarms of these little airborne devices could locate vehicles and movable objects of interest and attach themselves to these vehicles, feeding back location and other sensor information. Issues that will affect (positively or negatively) the evolution of these devices include:

Deployment/Launch/Propulsion/Recovery

- Increased range is important

Terrain/Medium/Environment

- Movements can be made in three dimensions as well as in pitch, roll, and yaw, allowing many more options for obstacle avoidance.
- Significant efforts have been made to develop sensors to support human flight in Category 3[13] (extremely poor visibility) conditions that provide the significant portions of the perception information in a computer usable format.
- Flight control systems for manned vehicles can already fly a complete route without intervention from a human. Many of the technological issues

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[13] Canadian Manual of Operations for Air Traffic Control

surrounding point A to point B flight have been solved. Higher-level problems of autonomy such as flight/mission planning remain.

- Military missions will add more challenging flight profiles for which commercial flight control systems are not designed. For example, military missions could involve threat avoidance and attack flight profiles.
- Integration with commercial air space will require automatic response to the human Air Traffic Controller, acceptance of flight profile changes assigned by the Air Traffic Controller, etc.

Capability/Task/Weapons

- Payload has a significant effect on size of the airframe required.

Navigation/Communications

- Adversarial electromagnetic interference

Robustness/Maintenance

- Dependent on expendability profile

Force Integration

- Integration with civilian air space

Scale Effects

- Increased vulnerability to turbulences as airframe size is decreased
- Level of sensors fidelity, accuracy, etc. decreases with reduced size
- Require low Reynolds number research
- Expensive as scale approaches full-size aircraft

2.3 Ground

Unmanned ground vehicles can assist in a number of roles including reconnaissance, path clearing, supply convoy duty (initially as a vehicle to convey payloads and eventually as a protecting force for the convoy), firefighting, etc. Medium-sized ground vehicles would provide unit level recognizance, sentry duty and mule duty. Smaller vehicles would provide cave reconnaissance, urban area recognizance, land mine detection and removal, etc. Smaller robots that are delivered to an operational location in a marsupial-like fashion could provide a multi-spectral, multi-sensor investigation and assessment of damage and threat. When weapons are added to these robots, additional hunter/killer tasks become possible. Unique issues confronting ground vehicles are:

Deployment/Launch/Propulsion/Recovery

- Recovery may be difficult if vehicle is damaged in adversary's territory
- Propulsion may be via articulated walking, tracks/wheels that are torque-driven, or a direct thrust platform – mounted on tracks or wheels (see Section 5.1.3)

Terrain/Medium/Environment

- Constrained paths
- Identification of traversable path
- Clutter/Obstacles

Capability/Task/Weapons

- Significant AI efforts required in order to deploy weaponry. The system will need to understand rules of engagement, detect targets and have earned the trust of the human commanders.

Navigation/Communications

- Trade-off between AI and degree of communications required
- Navigation requirements manageable providing path optimization can be developed
- Cluttered environment makes navigation (and autonomy) an order of magnitude more complicated than path planning and going from point A to point B as in the other battlespaces

Robustness/Maintenance

- Maintenance may be a challenge for certain applications; ground-based activity can cause a lot of wear and tear on a machine

Force Integration

- Difficult to get machines to behave as a squad, platoon, company, etc.
- Coordinating machines with humans requires even more effort.

Scale Effects

- Significant issues such as miniaturization (affects robotics, power, maintenance)

2.4 Marine

Marine robots refer to vehicles that perform on or just above the water's surface. These robots could perform activates such as convoy duty, search and destroy submarines, track and monitor enemy assets, detect and destroy mines, deliver small ground vehicles for covert operation. Challenges include:

Deployment/Launch/Propulsion/Recovery

- Vehicles can be stationed in the same medium (i.e., water) in which they operate (unlike UAV and UOV platforms which must take off or be launched)

Terrain/Medium/Environment

- detecting shorelines to enable detection of landmarks for navigation, to allow shoreline following, etc.
- pathfinding in shallow water with twisting channels
- robots will be unconstrained with regard to movement in two dimensions

Capability/Task/Weapons

- Platforms can be well-suited to carrying payload (high lift-to-drag ratio)

Navigation/Communications

- identify ships in various weather conditions
- drift and current impact on navigation

Robustness/Maintenance

- Buoyant force makes weight less of an issue (more robust, favours easier maintenance)

Force Integration

- Should be manageable, providing 21st century Command and Control exists

Scale Effects

- Miniaturization may be difficult – but perhaps not required to an extreme degree (still reasonable Reynolds numbers, payload etc)

2.5 Undersea

Undersea unmanned vehicles will play a role in searching for and detecting submerged mines, supporting divers, trailing enemy assets, etc. Being underwater adds new challenges to autonomous vehicles. These may include:

Deployment/Launch/Propulsion/Recovery

- Harsh environment
- Buoyancy problems
- Pressure

Terrain/Medium/Environment

- Pressure
- Currents
- Ice
- Visibility
- Corrosion

Capability/Task/Weapons

- Surveillance – manageable

- Weaponry – more difficult

Navigation/Communications

- Navigation, communications are difficult
- Stealth?

Robustness/Maintenance

- Manageable

Force Integration

- Difficult, due to communications issues

Scale Effects

- Acoustic signatures reduced with scale
- Capability reduced with scale also

2.6 Cyber

Battle in cyberspace is a recent phenomena and one in which there is no physical presence. This is an arena in which Canada and other First World nations have a higher vulnerability to attack than most potential enemies. It is an area where an ever-vigilant sentry with the ability to learn new attack strategies and to launch either evasive action or a counterattack is the only viable means of providing 24-hour protection of the assets. As the world becomes more connected, there will be more opportunities to identify targets of interest to suppress the operation of enemy networks, perform psychological attacks on the enemy population or track assets and assemble information of strategic interest.

Deployment/Launch/Propulsion/Recovery

- Targeting
- Launch techniques (distributed denial of service)

Terrain/Medium/Environment

- Open networks
- Closed networks
- Closed networks transitioning to open networks

Capability/Task/Weapons

- Computer network attack
- Computer network defence
- Computer network exploitation

Navigation/Communications

- IP address-based navigation
- Lack of discipline in IP address allocation can cause collateral damage
- Firewalls et al. affect communication
- Wireless and optical networks

Robustness/Maintenance

- Software maintenance, upgrade and support
- Intrusion detection and anti-virus software are a threat

Force Integration

- Distributed denial of service within cyber domain
- Swarming
- Possible to integrate cyber attack with other battlespaces

Scale Effects

- Easy-to-scale
- Swarming

2.7 Interbody

The potential for nanotechnology to allow the creation of devices that are capable of working inside the body will open a new battlespace.[14] These devices could be used in two forms, as a tool to enhance or fix the human combatant, or as a weapon against the enemy combatant or even their larger robots. At this point, these robots are a potentially disruptive technology that could provide unique and interesting capability due to their extremely small size. Once the ability to create nano computers and nano vessels has been developed (see Section 3.6 Nanobots) there will be significant effort required to enable mobility and provide a useful power plant for the device.

Clearly, such technologies have a myriad of policy implications. However, such implications are beyond the scope of this report.

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[14] Canadian National Institute for Nanotechnology Research Plan, Oct 2002

3 Current State of the Art in Robotics for UXVs

This section serves as a high-level introduction to the current state of the art in robotics. It begins with a very brief history, examines the commercially available robots and discusses recent areas of development (Alive, Cyberbots and Nanobots). Significant effort has been underway for many years on developing industrial robots which perform pick-and-place or welding type applications and are not mobile. This effort has resulted in many industrial standards for the design of such robots. These standards are listed in Table 8: Standards for Industrial and Commercial Robots and Table 9: ISO Standards for Industrial and Commercial Robots.

In terms of mobile robots, UAVs seem to have advanced at the fastest rate thus far. The reasons for this likely relate to the years of development in flight management systems and automatic pilot systems. As well, the UAV is not constrained by variable ground surfaces, etc. This leads to a much more structured operational environment. These factors have enabled the UAV systems to advance ahead of the more constrained UGVs.

There are currently 32 nations developing or manufacturing more than 250 models of UAVs; 41 countries operate some 80 types of UAVs primarily for reconnaissance.[15] This activity in UAVs is precipitated from the belief that these machines will eventually provide a cost-effective alternative to manned missions. UXV cost and expendability are highly dependant on scale. As UXVs approximate full scale, the cost of the vehicle is in the order of a manned platform cost. UXVs can approximate full-scale platform dimensions when the required payload of the vehicle is sufficiently large. In such cases, accommodation for a human being does not significantly alter the size of the vehicle. This substantially reduces the direct savings that would otherwise result from the unmanned focus of the design. Boeing's UCAV X-35C vehicle weighs 35,000 lbs, is 36 feet long and has a top speed of 0.85 Mach. The X-35C does not bear the hallmarks of an expendable UAV.

UXVs do offer cost savings in terms of personnel training and support. However, according to Dyke Weatherington of the US Office of the Secretary of Defense, the loss rate of unmanned vehicles is (currently) very high. This consideration complicates the economics of these vehicles. These loss rates are based on UAV data, but for the short- to medium-term, it would be reasonable to extend higher loss rates for UXVs in other battlespaces as well.

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[15] Unmanned Aerial Vehicles Roadmap 2002-2007, Office of the Secretary of Defense, pg 21

Table 8: Standards for Industrial and Commercial Robots

Group	Standard	Subject
1. ANSI/RIA	R1056-1986	American national standards for industrial robots and robot systems
2. BSR/RIA	BSR/RIA R15-06-19XX	Proposed standard for industrial robots and robot systems
3. ANSI/RIA	R15.02-1990	American national standard human engineering design criteria for hand-held robot control pendants
4. OSHA	Pub. 2254 (revised)	Training requirements in standards and training guidelines
5. NIOSH	Pub. 88-108	Safe maintenance guidelines for robotics workstations
6. OSHA	Pub. 8-1.3, 1987	Guidelines for robotics safety
7. OSHA	29 CFR 1910.147	Control of hazardous energy source (lockout/tagout final rule)
8. AFOSH	127-12, 1991	Occupational safety machinery

ANSI/RIA = American National Standards Institutes/Robotics Industrial Association
BSR/RIA = Bureau of Standards Review/Robotics Industrial Association
NIOSH = National Institute for Occupational Safety and Health
OSHA = Occupational Safety and Health Administration
AFOSH = Department of the Air Force

Table 9: ISO Standards for Industrial and Commercial Robots[16]

Standard	Description
ISO 8373:1994	Manipulating industrial robots – Vocabulary
ISO 8373:1994/Cor 1:1996	Manipulating industrial robots – Vocabulary
ISO 8373:1994/Amd 1:1996	Annex B – Multilingual annex
ISO 9283:1998	Manipulating industrial robots – Performance criteria and related test methods
ISO 9409-1:1996	Manipulating industrial robots – Mechanical interfaces – Part 1: Plates (form A)
ISO 9409-1:1996/Cor 1:1998	Manipulating industrial robots – Mechanical interfaces – Part 1: Plates (form A)
ISO 9409-2:2002	Manipulating industrial robots – Mechanical interfaces – Part 2: Shafts
ISO 9787:1999	Manipulating industrial robots – Coordinate systems and motion nomenclatures

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[16] http://www.iso.ch/iso/en/stdsdevelopment/tc/tclist/TechnicalCommitteeStandardsListPage.TechnicalCommitteeStandardsList?COMMID=4289

Standard	Description
ISO 9946:1999	Manipulating industrial robots – Presentation of characteristics
ISO 10218:1992	Manipulating industrial robots – Safety
ISO 10218:1992/Cor 1:1994	
ISO/TR 10562:1995	Manipulating industrial robots – Intermediate Code for Robots (ICR)
ISO/TR 11032:1994	Manipulating industrial robots – Application oriented test – Spot welding
ISO/TR 11062:1994	Manipulating industrial robots – EMC test methods and performance evaluation criteria – Guidelines
ISO 11593:1996	Manipulating industrial robots – Automatic end effector exchange systems – Vocabulary and presentation of characteristics
ISO/TR 13309:1995	Manipulating industrial robots – Informative guide on test equipment and metrology methods of operation for robot performance evaluation in accordance with ISO 9283
ISO 14539:2000	Manipulating industrial robots – Object handling with grasp-type grippers – Vocabulary and presentation of characteristics
ISO 15187:2000	Manipulating industrial robots – Graphical user interfaces for programming and operation of robots (GUI-R)

3.1 Short History

In one form or another, robots have existed for several hundred years. In 1688, General de Gennes built a Peacock that walked and ate. Jacques de Vaucanson built mechanical creatures, his most famous being a mechanical duck that paddled, quacked, extended its neck to take food and water and also defecated. Vaucanson also built humanoids. One played the mandolin, while simulating breathing, moved its head and tapped its feet; a second one played the piano and the third one played the flute. In 1815, Henri Maillardet built a mechanical robot that could write in both French and English and drew a variety of landscapes.

The technology advances which occurred in the 20th century, spawned new and more sophisticated robots. Between 1930 and 1950, various people built small autonomous robots out of electromechanical systems that could move towards a light source, attempt to move objects out of the way and, failing that, go around the object.

With the advent of digital computers, efforts to develop computer controlled robotics began in the late 1960s. Since that time, there has been a steady effort to develop autonomous robotic systems. This effort has resulted in the single- and multi-arm robotic systems commercially available in the industrial marketplace. Figure 4: Autonomous Control vs. Time presents a view of robotic efforts (specifically autonomous control) over time.

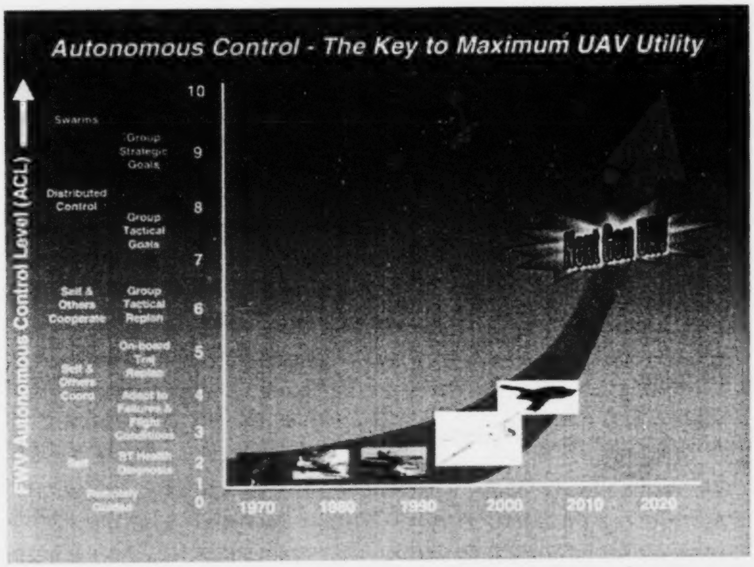

Figure 4: Autonomous Control vs. Time[17]

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[17] Applications, Concepts and Technologies for Future Tactical UAV's, RTO Lecture Series 224, pg9-7, Feb 2003

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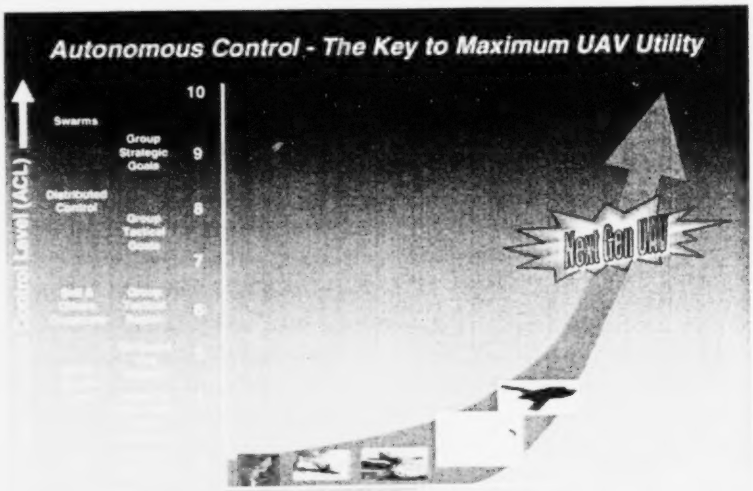

Figure 4: Autonomous Control vs. Time[17]

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Historically, robotic systems have exhibited a simple and repetitive ability to follow instructions. In particular, these robots have not exhibited any form of situational awareness or embodiment attributes that will be expected of fully autonomous robots. *Situational awareness* and *embodiment* are terms that are worthy of note. Rodney A. Brooks defines these terms as follows:

> "A situated creature or robot is one that is embedded in the world, and which does not deal with abstract descriptions but, through its sensors with the here and now of the world, which directly influences the behaviour of the creature.
>
> An embodied creature or robot is one that has a physical body and experiences the world, at least in part, directly through the influence of the world on that body. A more specialized type of embodiment occurs when the full extent of the creature is contained within that body."[18]

Today, there are robotic systems that are capable of traversing a boundary-defined area and performing tasks such as mowing the lawn or vacuuming the floors of the house, and there will soon be commercially available robots to clean windows.

3.2 Two Approaches to Intelligent Behaviour

Leading-edge robotic research at MIT and Stanford focuses on developing situated and embodied robotic systems. Two fundamentally different approaches have been followed to create cognitive or situated robots. The first approach is based upon a complete world model as defined below and the second is based upon layers of specialized functions in a subsumption architecture also defined below.

World Model Based Architecture

Dr. John McCarthy and Dr. Marvin Minsky formulated the first approach. This approach attempts to create a complete and consistent knowledge of the world the robot is to function in, then to internally (using a data storage device) maintain an accurate and up-to-date representation of this world over time. With this knowledge, task execution can be planned and the progress measured against the plan. With learning functions added to this architecture, the system can learn about its surrounding and adapt to change.

An example of how this would work is when going for a walk you would first map out the route in terms of the location of rocks, pot holes, the slope of the paths, turns and curves, etc. Then you would plan every foot placement along the way and the actions required by the body to make these steps. During the walk, you would follow this plan while checking that the details of the route continue to map directly to your world model. If a change occurs, you would then update your world model and develop a plan to deal with the change. This would allow you to get back onto your original planned route and execute that change.

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[18] Flesh and Machines: How Robots will change us, Rodney A. Brooks, 2002

Subsumption Architecture

The second approach has been developed by Dr. Rodney A. Brooks of MIT and his graduate students and is known as the "Subsumption Algorithm." The basis for this approach is that there are simple systems dedicated to controlling one part of the robot. There are layers above this that handle specific functions and send instructions to the lower level systems.

Using the example of taking a walk, the approach would be to plan to walk for a mile following the road and then turn back and return. The task of walking would be assigned to systems that only deal with walking and avoiding falling down or hitting objects (this activity could be performed by several systems). Higher-level systems monitor the world for events that may require action, a curve in the road, objects such as rocks and potholes. This system sends a command to the walking systems to avoid the obstacle. Still higher-level systems monitor the world for significant events, oncoming traffic, etc. and send commands to lower-level systems that then send commands down to still lower-level systems.

Many AI paradigms such as knowledge-based systems, inductive reasoning, blackboard architecture, neural networks, genetic algorithms are used to implement both approaches to intelligent machines.

Research efforts continue on both approaches at a large number of universities in Canada, the US and around the world. Stanford is still the leader in research into world modeling while MIT leads the efforts into the subsumption architecture. In particular, as processing power continues to improve and the capabilities of both approaches increase, there will likely be a convergence of the two approaches. This convergence is anticipated since the behaviour of humans when performing complex tasks tends to be a merger of these two approaches. When humans walk, they do not think about the actions the body must make to move one foot in front of the other except under extremely difficult situations. However, when a human decides to go from point A to point B, the process is typically to reason out a high-level plan and then the body executes the walking without much conscious thought, although monitoring and adaptation may occur which can result in adaptations to the body's movements.. The Minsky approach will provide the high-level goal driven and reasoning portion of the intelligence while the Brooks approach will provide the robust and adaptable control layers of the robot.

3.3 Emergence of Single Mission Robots into Everyday Life

Single-mission, fully autonomous robots have become commercially available in the last few years. These robots began with the release by Hasbro Corporation, the world's second largest toy company, of the toy "Furby." This is a small robot in the shape of a troll that has a number of sensors and responds to the surrounding world with a combination of verbal and motion responses.

This was followed by the release of the Robot dog AIDO by the Sony Corporation. This robot has four movable legs, a moving head and tail. It is able to sit, walk and chase balls. Many owners of this robot believe it has the ability to recognize people and respond to their commands even though this capability was not programmed into the robot. A number of these owners have anthropomorphized these robots into real dogs and treat them as such. At this point, the authors are not aware of any studies on the physiological aspects of this response to the behaviour of the robots. This has demonstrated that with an approach based upon building the behaviour bottom up using finite state machines with a defined focus, extremely life-like behaviour is possible – behaviour that humans can easily attribute to intelligence.

In the year 2000, Hasbro Corporation released a toy called "My Real Baby" which was a simple robot in the shape of a baby. This toy had various sensors which allowed the program to determine how the doll was being played with. The doll reacted to this knowledge with either happiness or tears. The doll had an internal emotional model that allowed the doll to become upset, happy, hungry or virtually damp. This robot acted very much like a small baby. The initial prototype was considered to be too lifelike to be a good doll and as a result, the behaviour model was simplified to create a more child friendly toy. The initial prototype would decide that it had not been fed recently enough, it would begin to cry and would not stop crying until it was fed. The longer it went without being fed, the more of a fuss it made. This behaviour was modified so that the doll stopped crying if it had not been responded to in a predetermined time or if it was played with in some other fashion. Thus the doll would forget it was hungry. This robot has demonstrated that the ability to incorporate very deep human traits into a machine action can be achieved. It also demonstrates that one problem which humans will experience with intelligent machines is the tendency to accept the behaviour as intelligent – without question.

Also in the year 1999 the first autonomous robotic tool (http://www.friendlyrobotics.com/) was released on the commercial market. This tool was an automatic Lawn Mower($300 – $2000US depending on the model). It required an electronic fence around the area to be mown to allow the mower to constrain the space it was to work in. Once activated, this robot would randomly mow a path. When it hit the electronic fence, it followed the inside of the fence for a while and then randomly set off in a direction inside the fenced area. Over time, the complete area is mowed. The next production development is a fully automated surface cleaner. This appliance is designed for domestic use and is intended to provide daily housekeeping assistance by keeping the major areas in the home constantly clean. The product will be equipped with a powerful vacuum cleaning head that is effective on carpets as well as hard surfaces. Entire room cleaning as well as local (spot) cleaning modes will be available. Future products envisioned by this company include a robotic snow thrower, an in-house security and surveillance robot, and perhaps one day a "personal helper" which can bring your meals to the table, clean after you and even dispose of your garbage.

Electrolux, Karcher, Dyson, Minolta (all vacuum cleaner manufacturers) and iRobots (a spin off company of the MIT robotics Lab run by Rod Brooks, developing commercial robots) are all about to release an autonomous vacuum cleaner for the home market. This robot will wander through the house cleaning the floor. Future versions will detect when humans are walking around and either avoid those parts of the house or return to base, recharge and work after the humans have left the area.

In the pipeline at iRobots are mini robots to clean under furniture and other robots to clean windows, windowsills and counters. These robots could be commercially available by 2006. They will be the first commercial application of swarming robots. The idea is to have a swarm of small robots constantly cleaning a designated area. Also commercially available are small remote presence robots (iRobot-LE)Figure 5: The Co Worker. These robots can map out the structure of a home and are able to move throughout the home. They have cameras mounted on long "neck-like" structures which can be raised and lowered to change the elevation, tilt and pan of the camera. The robot is controlled via an interface over the World Wide Web. High-level commands to travel to a location or move the camera, etc. are sent over the Web, and the video image from the camera is returned to the user's browser.

Figure 5: The Co Worker

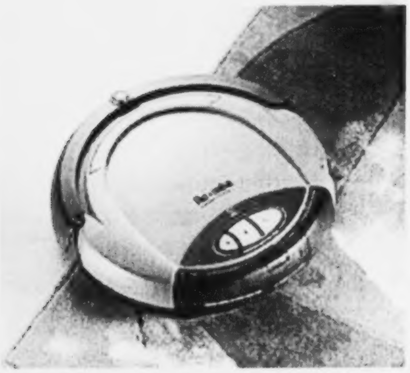

Figure 6: Roomba Vacuum from IRobot

The Roomba Robot Floor Vacuum from iRobot ($199US), shown in Figure 6: Roomba Vacuum from IRobot will vacuum your carpet and terrorize your pets while you relax and surf the Net. The Roomba will run about 1.5 hours on a charge, long enough to do three average size rooms. You can purchase an optional virtual wall to keep Roomba out of areas where you don't want it to go. Roomba starts off its cleaning in a spiral pattern. When it comes in contact with a wall or object, its wall-following sensor kicks in. Roomba has a cliff sensor to keep it from falling down stairs. Its low profile allows it to go under chairs, beds and furniture, at least four inches above the floor, places normally ignored with a regular vacuum. If the Roomba gets stuck, it will ping periodically and then eventually will shut itself off as a power-saving activity.

Demeter[19]

Core Description

The Demeter system strives to provide three levels of automation to harvesters, and eventually to tractors and combines. First, a "cruise control" feature, which will automatically steer, drive and control the harvesting header, will be provided to harvester operators. This feature will allow the operator to focus on other in-cab controls and harvest conditions, and to better handle contingency situations. Second, a "drone" feature will be provided, allowing one operator to remotely control several harvesters. Third, a fully autonomous machine will be developed which will allow a harvester to completely harvest a field with no human supervision.

Benefits

The first two levels of the Demeter system allow fewer, less-skilled operators to provide performance equal to or better than the current harvester performance on the average farm. At the final level of automation, performance will be maintained with no human supervision.

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[19] http://www.rec.ri.cmu.edu/projects/demeter/

Approach

The Demeter project uses off-the-shelf, proven technologies to provide an average guidance accuracy of +/-3 centimetres. State-of-the-art software algorithms are used to fuse data from multiple sensor sources, yielding a highly reliable and robust system.

Status and Commercialization Plan

The first level of automation has been verified on a New Holland 2550 Windrower. Current development includes improving and porting this technology to later Windrower models such as the HW340.

Sponsor

NASA and New Holland, Inc. initially sponsored the Demeter project, but as the project matured, NASA contributions decreased and New Holland contributions increased. Currently, Case-New Holland, Inc. (CNH) solely funds the Demeter project.

Contact

John Bares/ Ten 40th Street/ Pittsburgh, PA 15201/ TEL: (412) 681-6382/
Contact John Bares

The following is a list of competitions around the world for autonomous vehicles.
.007 MIT's remote-controlled robot competition
6.270 MIT's autonomous robot design competition
AAAI Mobile Robot Competition From the American Association for Artificial Intelligence
Aerial Robotics Competition This is the place for smart helicopters and blimps
All Japan MicroMouse Contest Micromouse maze running in Japan
All Japan Robot Sumo Worlds largest robot competition with 4000 robots entered!

AMD Jerry Sanders Creative Design Contest Autonomous or radio-control ball collectors
BattleBots The most dangerous collection of battling robots in the world
BEAM Their minimalist approach to robotics results in simple robots and fun competitions
BEST Boosting Engineering, Science and Technology through Robotic Competition
Bot Bash People who like to build robots and then go out and smash them into each other
BotBall Teams of High School students design, build and program a mobile robot
Canada First Robotic Games Sponsored by businesses to motivate students and expand the pool of "technology literate" graduates
Carnegie Mellon Mobot Races MObile roBOTs
Central Jersey Robo Conflict 12-pound remote controlled devices in competitive and combat-oriented games
CIRC Autonomous Sumo Robot Competition By the Central Illinois Robotics Club
Critter Crunch A robotic combat in which the object is to immobilize your opponent or to push him out of the arena
DragonCon Robot Battles Immobilize your opponent
EuroBot Annual autonomous robot competition in France
FIRA Robot World Cup International Robot Soccer
Fire Fighting Robot Contest Autonomous robots extinguish fires in a maze
FIRST Corporations sponsor local high schools across the US
Intelligent Ground Robotic Competition Annual competition with almost $15,000 in prize money
Knex K-Bot World Championships
Manitoba Robot Games Large Canadian competition
Micro-Rato In Portugal
Micromouse Competition The UC Davis Micromouse page
Mid US Robotics Club Robot Combat in the Midwest and Rocky Mountain states
Midwest Robot Competition Fighting Robots in the Midwest
NC Robot Street Fight In North Carolina
Northeast Indiana Robot Games Three weight classes of Robot Sumo Mayhem
Northeast Robotics Club Combat robotics in the Northeast
Northwest Antweight Competition Tiny fighting robots
Northwest Robot Sumo Tournament One of the biggest American sumo competitions
OCAD Sumo Robot Challenge Bashing/crashing/smashing robots
RI/SME Student Robotic Engineering Challenge
Robocide Fighting robots in Florida
RoboCup The official home page for the international Robot Soccer competition
RoboFesta International Robot Games Festival
RoboFlag Autonomous Mobile Robots Playing Capture The Flag
RoboJoust Producers of the Las Vegas Street Fights
RoboRama Robot competition sponsored by the Dallas Personal Robotics Group
Robot Battles Head-to-head combat with other 'bots
Robot Club & Grill The best meal you've ever had behind bulletproof glass
Robot Conflict Robotic Battles on the East Coast

Robot Riots Combat robots in Canada
Robot Sumo The annual competition held at the Exploratorium in San Francisco
Robot Wars A UK TV show
Robot Vacuum Cleaner Contest Fastest robot to vacuum 1/2 pound of rice wins
Robothon The annual competition of the Seattle Robotics Society
Robotica Robot mayhem in Portugal
RSSC Robot Competition Robotics Society of Southern California
S.E.R.C. South Eastern Combat Robotics
Singapore Robotic Games Eleven different competitions including legged robot race, wall climbing and "robot battlefield"
Steel Conflict Robots with attitude
Trinity LEGO Cybernetics Challenge A game of robot volleyball between teams of two robots built using Lego Mindstorms
Twin Cities MechWar Mayhem in Minnesota
USA Robot Sumo Japanese champions come to the US! $2000 first prize.
UMAL Upper Midwest Antweight League – tiny fighting robots
Underwater Robotics Competition If you think that 2D navigation is difficult, try 3D!
Walking Machine Challenge SAE Student competition
Western Canadian Robot Games Canada's premier robotic event includes Robot Sumo, BEAM and Robot Hockey

3.4 Artificial Life

The term "Artificial Life" is used to describe research into human-made systems that possess some of the essential properties of life. As it turns out, there are many such systems that meet this criterion – digital, test-tube, and mechanical – and these can be used to perform experiments aimed at revealing the principles and the organization of living systems on Earth as well as elsewhere. This effort is truly interdisciplinary and runs the gamut from biology, chemistry and physics to computer science and engineering. While a large part of Artificial Life is devoted to understanding life as we know it – that is, life on earth – a significant effort concerns the search for principles of living systems which are *independent* of a particular substrate. Thus, Artificial Life also considers life "as it could be," exploring artificial alternatives to a carbon-based chemistry.

Artificial Life is often described as attempting to understand high-level behaviour from low-level rules; for example, how the simple rules of Darwinian evolution lead to high-level structure, or the way in which the simple interactions between ants and their environment lead to complex trail-following behaviour. Understanding this relationship in particular systems promises to provide novel solutions to complex real-world problems such as disease prevention, stock-market prediction and data-mining on the Internet. The methodology has already helped resolve cargo routing efficiencies at SouthWest Airlines; communications traffic bottlenecks at British and French Telecom.

The construction of living systems out of non-living parts is clearly the most ambitious of all the areas of Artificial Life. At present, this subfield is split into two largely independent endeavors: the creation of life using the classical building blocks of nature (carbon-based life) and the creation of life using the same principles but a different medium for implementation: the computer. The former explores the possibility of "RNA worlds" by attempting to construct self-replicating molecules; the latter, by simulating simple populations of self-replicating entities, examines the abilities and characteristics of different chemistries in supporting lifelike behaviour. Thus, both the biochemical and the computational approaches seek to shed light on the compelling question of the origin of life.

Yet Artificial Life is not only about the construction and simulation of living systems, whether artificial or natural; an impressive engineering effort is geared towards the construction of adaptive autonomous robots. This work differs from the classical robotics approach in that the robotic agent interacts with its environment and learns from this interaction, leading to *emergent* robotic behaviour. Further information on current activities and upcoming conferences can be viewed at these URL, http://alife.org/index.php?page=alife7&context=alife7, http://www.cs.umn.edu/alife/index.html.

During the 1990s, a branch of AI/biology/robotics began to develop simulated evolving software-based life forms. The intent of this research was to look at learning behaviour in the same fashion that biologists believed that human intelligence evolved. This began with the development of genetic algorithms, a technique for allowing software programs to combine to create a new program containing parts of both programs. Based upon the ability of the new offspring program to function within a set of constraints, the program is allowed to replicate with another program. By beginning with a large number of programs and allowing them to replicate, resulting programs can be optimized for the problem space.

Several researchers, such as Dr. Tom Ray, currently at the University of Oklahoma as a Professor of Zoology and Computer Science, Karl Sims[20] (who currently leads GenArts, Inc. in Cambridge, Massachusetts) Jordon Pollack (Associate Professor, Computer Science Department, Center for Complex Systems, Brandsis University, http://www.demo.cs.brandeis.edu/index.html) and Rod Lipson have treated these programs like evolving creatures, provided them with a task to perform, and have assessed the ability of the "creature" to perform this task. Based upon their performance, high-scoring "creatures" are permitted to replicate and create "offspring." Recent work has used replication technology to enable the resultant "creature" to be built and tested. The results of the "creatures" working in a "non-computer" environment were then used to grade the resultant offspring and direct the evolution.

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[20] "Evolving Virtual Creatures"
K.Sims, Computer Graphics (Siggraph '94 Proceedings), July 1994, pp.15-22.
"Evolving 3D Morphology and Behavior by Competition"
K.Sims, Artificial Life IV Proceedings, ed.by Brooks & Maes, MIT Press, 1994, pp.28-39.

These experiments have created very optimum "creatures" for the "world model" that the "creatures" lived in. However, it has not created a "creature" capable of new and additional things outside of the criteria used to select the best. It has been suggested that either there are underlying issues that are not yet understood about biology and evolution or that there is just not enough computing power, etc. to allow these "creatures" to evolve.

An additional issue may be that the environment being used is too simple. There are not competing evolutionary success factors. When a "creature" begins to lose to an evolutionary pressure, there is no reason for that "creature" to begin to compete in a different environment. There is no constraining the "change of the creature," for example, when a "creature" develops long arms; losing them in a generation is not likely, as it would happen over a number of generations. Further, there will be the occasional throwback in the programming to reintroduce lost capabilities. This richness of the evolution constraints does not appear to exist in the models currently being used.

Such technology has the potential to create totally disruptive capabilities for robotics and software if the current problems with the evolutionary models are eventually overcome. Combining this technique for creating the software algorithms within a fixed robotic platform may provide significant enhancements in the ability of the various portions of the robot control and higher-level systems to develop advanced capabilities and adapt to changes over time. This technology could enable software created for a specific hardware platform to evolve its ability to perform various tasks utilizing the sensors and actuators available to it.

Recent efforts include:

Hornby, G.S., Takamura, S., Yokono, J., Hanagata, O., Fujita, M. and Pollack, J. (2000). **Evolution of Controllers from a High-Level Simulator to a High DOF Robot**.
Miller, J. (ed) *Evolvable Systems: from biology to hardware; proceedings of the third international conference (ICES 2000)*. Springer (Lecture Notes in Computer Science; Vol. 1801). pp. 80-89.
Pollack, J. B., Lipson. H., , Ficici, S., Funes, P., Hornby, G. and Watson, R. (2000). **Evolutionary Techniques in Physical Robotics**.
Miller, J. (ed) *Evolvable Systems: from biology to hardware; proceedings of the third international conference (ICES 2000)*. Springer (Lecture Notes in Computer Science; Vol. 1801). pp. 175-186.
Hornby, G.S. and Mirtich, B. (1999). **Diffuse versus True Coevolution in a Physics-based World**.
Proceedings of 1999 Genetic and Evolutionary Computation Conference (GECCO). B\anzhaf, Daida, Eiben, Garzon, Honavar, Jakiela, Smith, eds., Morgan Kauffmann, pp. 1305-1312.
Pollack, Jordan B., Lipson, Hod, Funes, Pablo, Ficici, Sevan G. and Hornby, Greg (1999). **Coevolutionary Robotics**.
The First NASA/DoD Workshop on Evolvable Hardware (EH'99). John R. Koza, Adrian Stoica, Didier Keymeulen, Jason Lohn, eds., IEEE Press.

3.5 Microbots

This term refers to miniature robots which are measured in centimetres. These robots require extensive miniaturization of, or the creation of all new sensors, actuators and propulsive engines. Extensive effort is underway at Berkley and other universities in the US to create small fly-size robots that will be able to fly using wings that beat to the same rhythm and process followed by real fly wings. Scale models have been developed to verify the ability of the beating algorithms. Currently, new mechanisms for activating the movement of the wings are being developed at the scale necessary to build this device.

Work is also underway to create small disk-shaped devices that will fly. The National Research Council of Canada is working to overcome one of the hurdles for this device, reducing the drag with new materials.

One interesting effort for energizing small robots was the development of a small robot to search a garden for slugs. This robot would pick up any slugs it located and place them in an acid-filled tub. The resultant gases were then captured and used in a fuel cell to provide the power for the robot in its search for more slugs.[21]

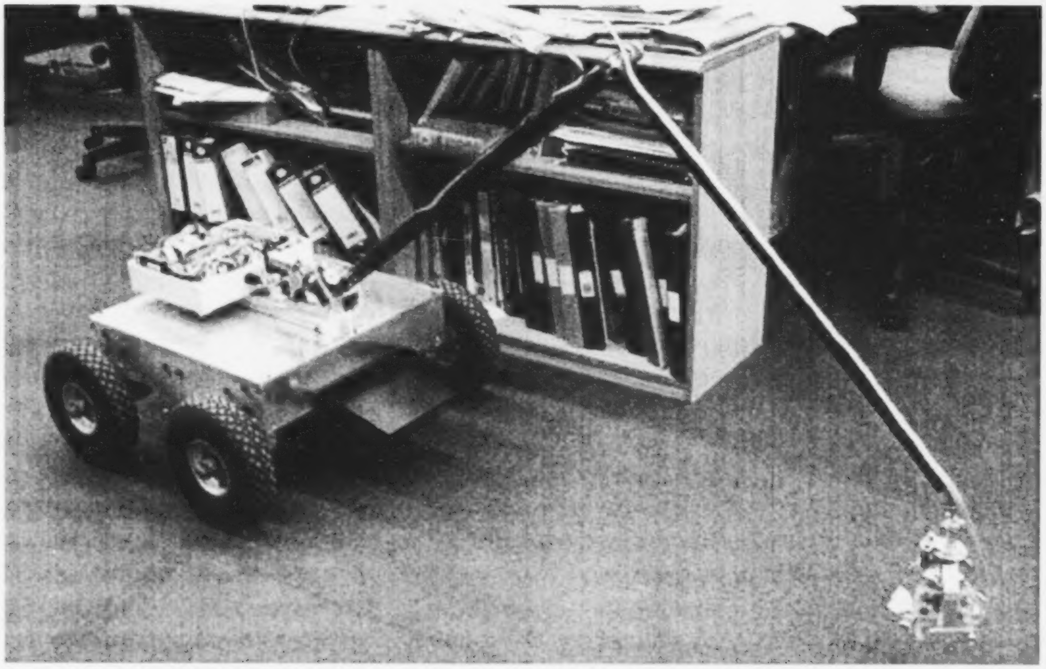

Figure 7: Slugbot

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[21] University of West England Intelligent Autonomous Systems Lab, 2000 http://www.ias.uwe.ac.uk/goto.html?slugbot

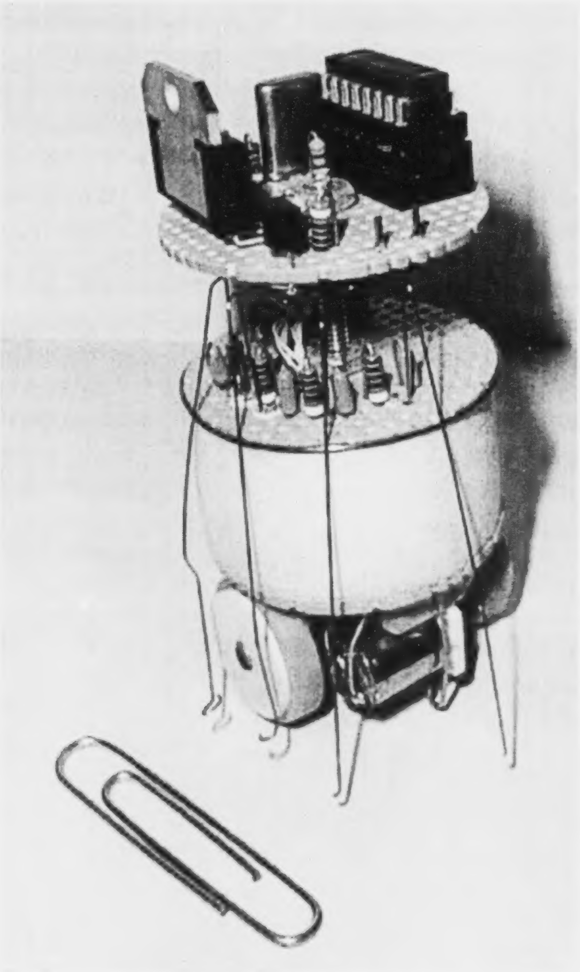

Figure 8: Micro Size Robot

The robot shown in Figure 8: Micro Size Robot was designed to compete in the "BEAM" Nanomouse robotic competition. As can be seen in the picture, the Nanomouse is a scaled-down version of the popular Micromouse type events held all over the world.

This particular mouse was the only one to successfully complete the maze, in any amount of time, so it took first place both years it was entered.

The mouse uses the Motorola 6805kics microcontroller and a National Semiconductor 1 amp dual H-bridge motor driver I.C. The drive train consists of two modified micro servers used for very small RC planes. The motors are placed in the standard opposing positions so that the mouse can rotate on its axis. Power is provided by four 110 ma NiCad batteries housed in the pink body portion of the mouse. These can be recharged between runs. Sensing is accomplished by four piano wires that, when touching a wall, come in contact with a copper strip placed along the waist of the mouse. This in turn will activate the microcontroller inputs and the appropriate action will take place.

3.6 Nanobots

Nanobots will be robots created at the atomic level and will be nanometers in dimension. The concept of nanotechnology has been around for some time. In 1981, Nobel prize winner Dr. Roald Hoffmann made the following comment, "What is exciting about modern nanotechnology is (a) the marriage of chemical synthetic talent with a direction provided by 'device-driven' ingenuity coming from engineers, and (b) a certain kind of courage provided by those incentives, to make arrays of atoms and molecules that ordinarily, extraordinary chemists just wouldn't have thought of trying. Now they are pushed to do so. And of course they will. They can do anything. Nanotechnology … is the way of the future, a way of precise, controlled building, with incidentally, environmentally benignness built in by design."[22]

Effort has been underway since that time to develop the ability to manipulate atoms and molecules. The early work involved pushing atoms around using scanning tunneling microscopes. In the November 1999 issue of *Science,* it was reported that H. J. Lee and W. Ho, researchers at Cornell University, had bonded a single carbon monoxide molecule to an iron atom. This event has triggered dramatic growth in this technology.

There have been several nano tools built that are designed to pick up or move atoms and molecules. There is even discussion about a nanocomputer being built as early as 2006.[23] This technology is being investigated to create propulsion devices that move by anchoring one end of a carbon chain, then squeezing the chain together like an accordion, anchoring the tail end and straightening the chain in an inchworm effect. The shorter-term effect of this technology has been to create new materials with massively improved properties of strength, reforming, etc. Future capabilities could include self-repairing material, ultra-light and extremely strong material, contracting and expanding material, etc.

Within the technical and academic community working in nanotechnology, there is continuous insistence that small devices will be able to be created. These devices could be self-replicating and will be able to deliver services to portions of the human body. These services would include cell repair, drug delivery, attacking viruses and foreign agents in the bloodstream. It is too early in the technology stream to know if these nanobots will be created. What can be said with some certainty is that if these nanobots do become viable, it is not unreasonable to expect this to occur in the next 20 years. If these devices are created, then it is likely that they will exist as a result of a convergence of bio processes, quantum mechanics and organic chemistry. Such devices could provide capabilities for engine fault correction, sensor repair and many other functions on UXV structures.

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[22] The Spike, How our lives are being transformed by rapidly advancing technology, Damien Broderick, 2001

[23] Dr.Stan Williams of Hewlett-Packard Feynman Laboratories, 1999

3.7 Cyberbots

Cyberbots are computer programs/agents that have the ability to move throughout cyberspace and perform various missions. These programs can be hosted on one or more computers and move through cyberspace performing their mission from the host. Alternatively, these programs can move through cyberspace looking for an opportunity to latch onto computing resources that can be used to further execute the program's mission. These programs are capable of replicating themselves as well as mutating with time or number of replications.

Cyberbots have existed for a number of years. Search engines to harvest URLs, e-mail addresses and other information from computers in the World Wide Web already use these software programs. Other forms of cyberbots include viruses, worms and "denial of services" programs aimed at attacking computers within the cyber world. Cyberbots have been used to respond to cyber attacks by attacking the virus or the programs. They have also been used in conjunction with Alive (genetic) algorithms to test for vulnerabilities in computer networks. A list of existing cyberbots is provided in Appendix A.

3.8 Commercialization of the Autonomous Robotics

The enabling technology streams are clearly vital if UXVs are to be deployed in the future. Commercialization of the output from these streams will also be required to effectively advance the technology. How does one determine the proximity to commercialization of a given technology stream development? This is a difficult task. At a minimum, there are three technology development paths towards UXV deployment:

- Direct-focus development;
- Modification of platforms developed by others;
- Integration of commercialized and non-commercialized sub-components.

The first path is essentially a brute force approach. The project leaders need to be empowered to develop and integrate whatever they need to achieve their desired goals. There are several examples of this in the history of technology. A dramatic case of this is the American Apollo program. Neither the science nor the technologies were in place to go to the moon in 1961. The infrastructure did not even exist. But a goal was set to land men on the moon prior to the end of the decade – and it was achieved. The cost, in today's dollars, was in the order of US$300 billion.

The second approach is simply a "buy and adjust" exercise. This is perhaps the easiest approach from a national effort viewpoint. However, it does little to develop national capabilities and the technology may not suit precise Canadian requirements.

The last approach has the hallmarks of a disruptive technology development process – although the other methods have disruptive potential also. This involves using existing technology components, putting them together in a unique way – and deploying them in a unique manner also. It is an integration and unique-use exercise and is probably a medium-cost solution.

To truly assess how close a technology is for DND's requirements, an assessment based upon the anticipated missions and battlespaces for the UXV will be required. Consideration of missions and battlespaces will have a dramatic impact on the commercialization path. Carrying out such an assessment is beyond the scope of this report.

This discussion underscores that a commercialization path for UXVs (particularly military-focussed) is very difficult to map. Enabling technologies may be developed solely for the UXV, they may be commercialized off-the-shelf components with a clear value proposition, or they may be some sub-system of a larger piece (middleware). Regardless, development within a given enabling technology stream can be monitored – and this provides an indication as to what options are available for UXV deployment.

4 A Road Map to Fully Autonomous Cooperative UXVs

In order to have a fully autonomous cooperative UXV, there is a fundamental requirement to have a platform that allows the UXV to travel, sense and affect change within its environment, sufficient to carry out any mission required of it. It is also necessary for this platform to be guided by an intelligence system which understands the mission and interprets the information regarding the physical world in which the UXV is active. Furthermore, the machine must be able to plan an approach to deal with achieving mission success despite any obstacles it may come across.

The platform must provide mechanisms for mobility, have its own power and should have an ability to monitor its own health throughout the mission. It should also be able to modify its performance characteristics or adopt to health problems in order to optimize its ability to complete a mission. Furthermore, any UXV participating in a military mission must provide a means for interacting with humans who might also be participating in the mission – as well as other UXVs and central command.

With the evolution of fully autonomous vehicles, there will be an ability to migrate from a centralized control architecture representative of today's UXV systems towards increasing decentralized control. When this occurs, an issue will arise regarding what information should be sent to central/mission control. The answer to this question will depend greatly on the mission profile.

Reconnaissance missions will require far more data to be returned than many hunter/killer missions (unless reporting is done by exception). The hunter/killer missions may only require a communication of the identified target and a request for approval to engage in hostile activities. Reconnaissance flights could provide a continuous live stream from several onboard sensors. An alternative to streaming sensor data back to the end-user would be to record the sensor data onboard. However, this would require additional space and could therefore limit the mission. The result is a trade-off between space and bandwidth. Another alternative would be to assess the data onboard; only data of interest to the mission would be stored or transmitted.

The live feeds would also be used by the perception and planning functions of the vehicle to execute the mission profile. No control signals would be sent between the mission command centre and the UXV unless the mission goal needed to be updated.

The general architecture developed by the US National Academy of Science can be seen in Figure 9: UXV Capability Requirements. This architecture is logically segmented into two portions: the first is the Autonomous Behaviour that provides the higher-level capabilities of the vehicle and the second is the UXV platform which provides the underlying structural capabilities that allow the first portion to interact with the world. These two elements loosely map to the world model and the subsumption architecture discussed in *Section 3.2: Two Approaches to Intelligent Behaviour*.

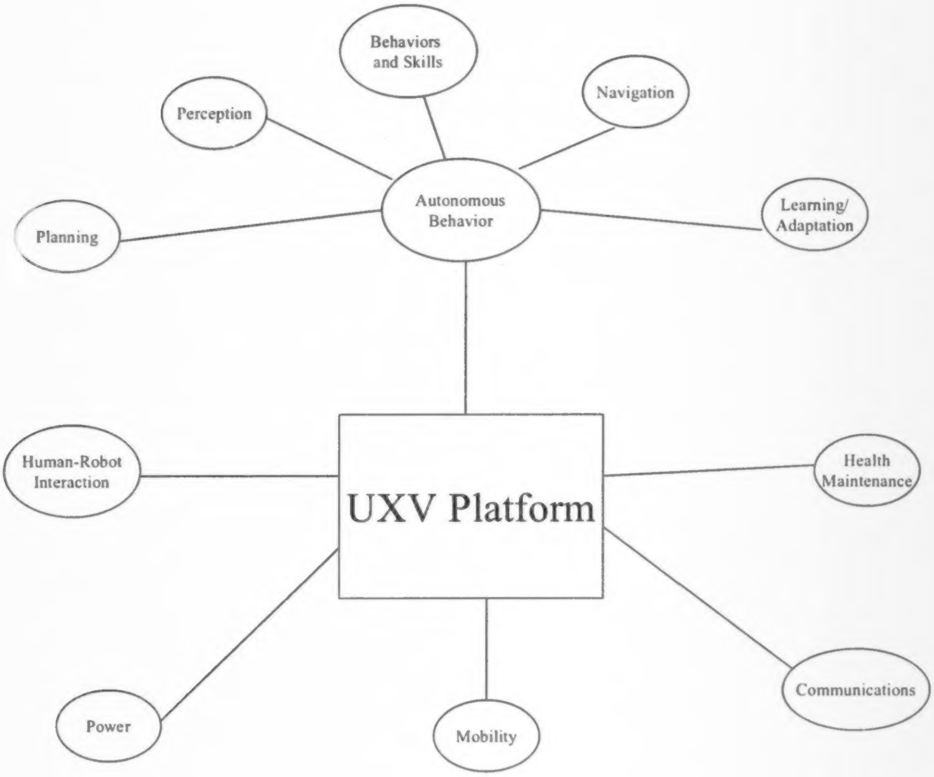
Behaviors and Skills
Perception
Navigation
Autonomous Behavior
Planning
Learning/ Adaptation
Human-Robot Interaction
UXV Platform
Health Maintenance
Power
Mobility
Communications

Figure 9: UXV Capability Requirements

The capability of the UXV to directly impact operational outcomes can be mapped into the UXV Technology Development Space. The technology development space defines the relevant dimensions associated with UXV deployment – and the impact thereof. In order to maximize the direct impact of a UXV on an overall operation, the following dimensions need to considered:

- Enabling technology development;
- Technology integration (the integration of the enabling technologies into a useful package);
- Mission complexity (the more complex the mission, the greater the direct impact on the overall operation).

Arguably, very simple missions, with loosely integrated enabling technologies, can make a significant impact on a given operation. However, historically, with some exceptions, the largest military impacts have been achieved with well-developed, tightly integrated technology and missions which required substantial planning/complexity. The interaction of these three dimensions is shown in Figure 10 UXV Technology Development Space.

In essence, this shows that with the increasing capability or maturity of the underlying technologies, for each of the architectural components of the UXV defined in Figure 10 UXV Technology Development Space, the missions that UXVs can perform will increase in complexity. It is worth noting that since both the Enabling Technology Development and Mission Complexity axes are multi-dimensional. An improvement in one of these sub-dimensions can result in significant enhancement to the mission profiles that can be undertaken. Furthermore, depending upon the mission requirement, different enabling technologies will have a larger impact on mission outcomes. For example, countrywide reconnaissance will require greater improvement in propulsion and fuel efficiency while a ground support system might require significant improvement in perception and target identification.

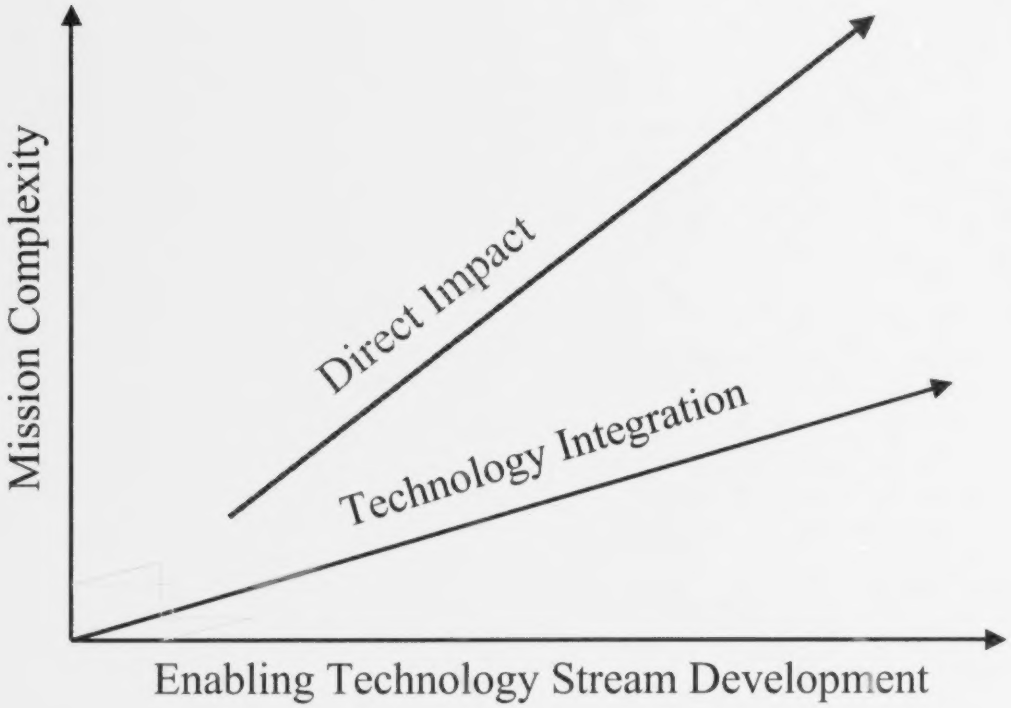

Figure 10 UXV Technology Development Space

The components of the general architecture that make up the Autonomous behaviour and the UXV Platform as well as technologies that will enable the emergence of new capabilities fall into the following *Enabling Technology Streams*:

- **Robotics, Dynamics and Mobility**
  - Propulsion Systems
- **Intelligent Software, Sensing and Navigation**
  - Planning, Perception, Behaviour and skills, learning and adaptation, health maintenance, human machine interactions
- **Control Systems**
- **Materials**
- **Communications**
- **Power/Energy Systems**

Fundamentally, these technology streams will require sophisticated integration. The development of the streams and associated integration efforts lead to more complex mission capabilities – and ultimately, increased direct impact on operational outcomes. An example of a UXV analysis based on operational outcomes is presented in Appendix B. The reader may find this approach useful for analyzing different UXV scenarios, technologies and outcomes.

The impact of increasing mission capability can be seen in Figure 11: Evolving Mission Profile Types This figure shows four types of UXVs with increasing levels of autonomy, perception, mission behaviour knowledge and capability. In theory, all four systems could have the same hardware platform with different software capabilities.

Each successive UXV has all of the capacity of the preceding level with the addition of new technological capabilities. The Telepresences system has the ability to move around and perform functions, but all reasoning about what to do and how to do it is made by a human who has a continuous live feed of all the sensor data and sends commands.

The Donkey is an autonomous vehicle that would be used to carry things for a human. Using sensor input, this UXV would follow a human and would determine where it should move. It would remain within a fixed distance of the human. Reasoning about what to do and how to do certain tasks are more advanced but still very basic. The ability to build systems that would provide the basic capability for some missions exist, as evident from the New Holland Harvester discussed in Section 3.

The Wingman/Scout would be able to autonomously venture forward and provide personnel with reconnaissance information about what is ahead. The ability to perceive the world around it would be quite advanced, but there is no capability to make tactical decisions or to identify targets and engage them.

The Hunter/Killer is a UXV that can be sent to perform a mission, identify targets and engage and destroy those targets.

The evolution of mission complexity can be seen in *Figure 12: Evolution of Mission Capabilities for Autonomous UXVs*. This figure continues on *from Figure 11: Evolving Mission Profile Types* The minimum capability shown in Figure 5 is that of a UXV performing one pre-programmed mission autonomously. This mission might be to clear out land mines in a specific location following a specific route – all of which is pre-programmed by the mission commander and monitored and corrected as appropriate. Once this capability has been thoroughly tested and the underlying technologies improved, the UXV may adapt the pre-programmed plan, during the mission, to accommodate necessary changes. For example, the UXV might determine that a portion of the terrain is not passable and devise an alternative strategy to circumnavigate the impeding area, while meeting mission goals.

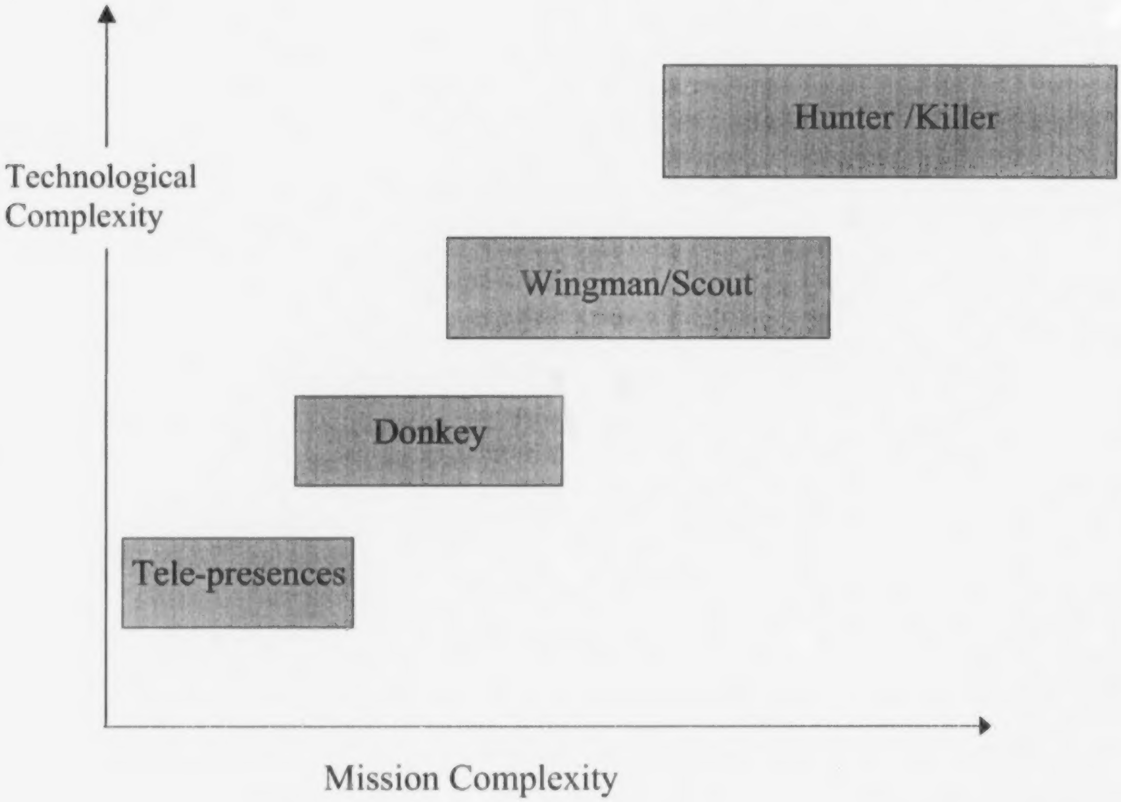

Figure 11: Evolving Mission Profile Types

The next logical step is to use multiple UXV's in the mission, allow the human to pre-program the approach, and allow some level of mission planning to be undertaken by the performing one pre-programmed mission autonomously. This mission might be to clear out land mines in a specific location following a specific route – all of which is pre-programmed by the mission commander and monitored and corrected as appropriate. Once this capability has been thoroughly tested and the underlying technologies improved, the UXV may adapt the pre-programmed plan, during the mission, to accommodate necessary changes. For example, the UXV might determine that a portion of the terrain is not passable and devise an alternative strategy to circumnavigate the impeding area, while meeting mission goals.

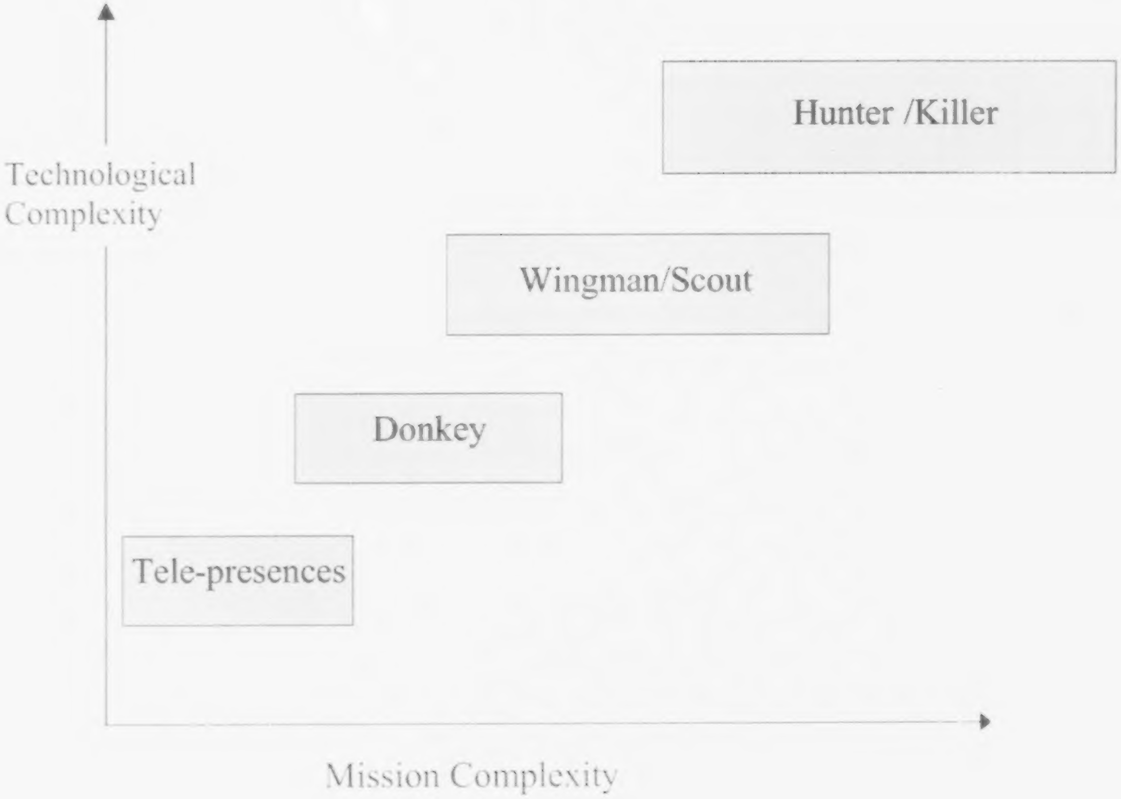

Figure 11: Evolving Mission Profile Types

The next logical step is to use multiple UXV's in the mission, allow the human to pre-program the approach, and allow some level of mission planning to be undertaken by the

UXVs, based on the actual conditions encountered during the mission. The technology could also evolve to enable the UXV to pre-plan its program to execute the assigned mission. Initially, this would likely require human verification. Once this capability is mature, it could be used in single mission multiple UXV type applications. This capability for planning a mission could also lead to the assignment of multiple missions to a UXV. In this instance, the UXV could plan all mission programming and adopt strategies and changes to the mission in progress depending on its situational awareness during the execution of the mission. This capability will lead to multiple UXVs working cooperatively and sharing some coordination and common goals. This evolution will continue creating ever more capable UXVs.

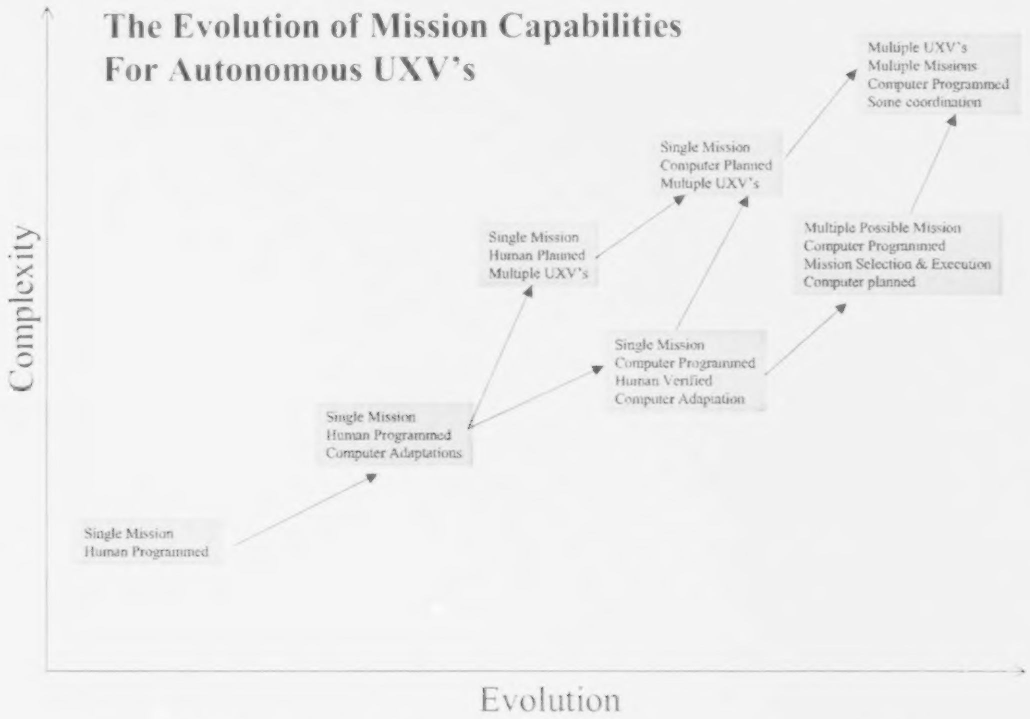
The Evolution of Mission Capabilities
For Autonomous UXV's
Complexity
Evolution
Single Mission
Human Programmed
Single Mission
Human Programmed
Computer Adaptations
Single Mission
Human Planned
Multiple UXV's
Single Mission
Computer Programmed
Human Verified
Computer Adaptation
Single Mission
Computer Planned
Multiple UXV's
Multiple Possible Mission
Computer Programmed
Mission Selection & Execution
Computer planned
Multiple UXV's
Multiple Missions
Computer Programmed
Some coordination

Figure 12: Evolution of Mission Capabilities for Autonomous UXVs

As with most technologies, increasing the complexity of missions requires optimization of certain components (i.e., enabling technology streams). Generally, this results in an increased optimization of the integrated package (although sub-optimization can occur if there is an excessive amount of focus on a particular component or outcome).

Increasing Optimization can be measured in terms of improvements in the relevant performance metrics. These metrics include:

- **Vehicle Scale**
- **Range and Endurance**

UXVs, based on the actual conditions encountered during the mission. The technology could also evolve to enable the UXV to pre-plan its program to execute the assigned mission. Initially, this would likely require human verification. Once this capability is mature, it could be used in single mission multiple UXV type applications. This capability for planning a mission could also lead to the assignment of multiple missions to a UXV. In this instance, the UXV could plan all mission programming and adopt strategies and changes to the mission in progress depending on its situational awareness during the execution of the mission. This capability will lead to multiple UXVs working cooperatively and sharing some coordination and common goals. This evolution will continue creating ever more capable UXVs.

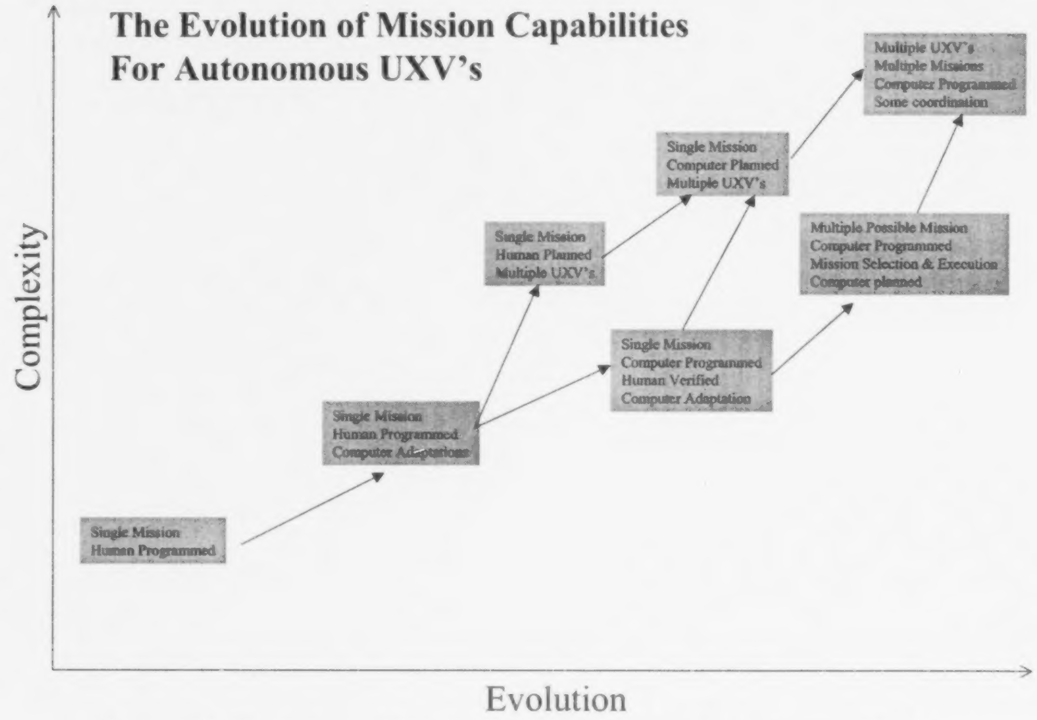
The Evolution of Mission Capabilities
For Autonomous UXV's
Multiple UXV's
Multiple Missions
Computer Programmed
Some coordination
Single Mission
Computer Planned
Multiple UXV's
Single Mission
Human Planned
Multiple UXV's
Multiple Possible Mission
Computer Programmed
Mission Selection & Execution
Computer planned
Single Mission
Computer Programmed
Human Verified
Computer Adaptation
Single Mission
Human Programmed
Computer Adaptations
Single Mission
Human Programmed
Complexity
Evolution

Figure 12: Evolution of Mission Capabilities for Autonomous UXVs

As with most technologies, increasing the complexity of missions requires optimization of certain components (i.e., enabling technology streams). Generally, this results in an increased optimization of the integrated package (although sub-optimization can occur if there is an excessive amount of focus on a particular component or outcome).

Increasing Optimization can be measured in terms of improvements in the relevant performance metrics. These metrics include:

- **Vehicle Scale**
- **Range and Endurance**

- **Maintainability**
- **Availability**
- **Reliability**
- **Survivability**
- **Payload**
- **Detectability (Stealth)**
- **Cost**
- **Autonomy**

These metrics are discussed in further detail in Section 6 of this report.

5 Technological Challenges to Overcome

It is estimated that the computing power available today is in the order of 1/100th of the computational ability of the human mind. Following Moore's Law, computers capable of performing with the complexity of the human mind will be available within 20 years. There are a number of technical and financial barriers to Moore's Law as discussed next.

> Technological Hurdles: *"Paul A. Packan, a respected researcher at Intel, argued last September in the journal* Science, *Moore's Law will "be in serious danger." Packan identified three main challenges. The first involved the use of "dopants," impurities that are mixed into silicon to increase its ability to hold areas of localized electric charge. Although transistors can shrink in size, the smaller devices still need to maintain the same charge. To do that, the silicon has to have a higher concentration of dopant atoms. Unfortunately, above a certain limit the dopant atoms begin to clump together, forming clusters that are not electrically active. "You can't increase the concentration of dopant," Packan says, "because all the extras just go into the clusters." Today's chips, in his view, are very close to the maximum.*
>
> *Second, the "gates" that control the flow of electrons in chips have become so small that they are prey to odd, undesirable quantum effects. Physicists have known since the 1920s that electrons can "tunnel" through extremely small barriers, magically popping up on the other side. Chip gates are now smaller than two nanometers – small enough to let electrons tunnel through them even when they are shut. Because gates are supposed to block electrons, quantum mechanics could render smaller silicon devices useless. As Packan says, "Quantum mechanics isn't like an ordinary manufacturing difficulty – we're running into a roadblock at the most fundamental level."*
>
> *Semiconductor manufacturers are also running afoul of basic statistics. Chip-makers mix small amounts of dopant into silicon in a manner analogous to the way paint-makers mix a few drops of beige into white paint to create a creamy off-white. When homeowners paint walls, the color seems even. But if they could examine a tiny patch of the wall, they would see slight variations in color caused by statistical fluctuations in the concentration of beige pigment. When microchip components were bigger, the similar fluctuations in the concentration of dopant had little effect. But now transistors are so small they can end up in dopant-rich or dopant-poor areas, affecting their behaviour. Here, too, Packan says, engineers have "no known solutions." Ultimately, Packan believes, engineering and processing solutions can be found to save the day."*[24]
>
> Financial Hurdles: *"But Moore's Law will still have to face what may be its most daunting challenge – Moore's Second Law. In 1995, Moore reviewed microchip progress at a conference of the International Society for Optical Engineering.*

> *Although he, like Packan, saw "increasingly difficult" technical roadblocks to staying on the path predicted by his law, he was most worried about something else: the increasing cost of manufacturing chips.*
>
> *"Capital costs are rising far faster than revenue," Moore noted. In his opinion, "the rate of technological progress is going to be controlled [by] financial realities." Some technical innovations, that is, may not be economically feasible, no matter how desirable they are.*
>
> *In the last 100 years, engineers and scientists have repeatedly shown how human ingenuity can make an end run around the difficulties posed by the laws of nature. But they have been much less successful in cheating the laws of economics. (The impossible is easy; it's the unfeasible that poses the problem.) If Moore's Law becomes too expensive to sustain, Moore said, no easy remedy is in sight."*[24]

If and when the current anticipated capabilities of Silicon, as shown in *Figure 13: Processor Speed Trends*, have been reached, there are a number of efforts that should lead to technologies that will exceed these silicon barriers. These technologies include GaAs Microchips and Optical processors that could become commercially viable in the 2003 –2007 time frame; Microcubes and Biochemical processors in the 2008 to 2017 time frame; and X-ray/Electron beam Lithography, Molecular Processors and finally the promise of Quantum and Nano computers in the 2018 to 2027 time frame.[25]

At this point, it is clear that there are barriers to realizing this computational complexity. Whether or not they are insurmountable is another matter. Over the last 30 years, technology breakthroughs have consistently crushed every anticipated technological barrier to the continuation of the 2^N increase in computational complexity. Currently, it appears that the computational capability available is doubling every 18 to 24 months – Moore's Law.

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[24] `http://www.imakenews.com/techreview/e_article000003598.cfm`

[25] Unmanned Aerial Vehicles Roadmap 2002-2007, Office of the Secretary of Defense, pg 43

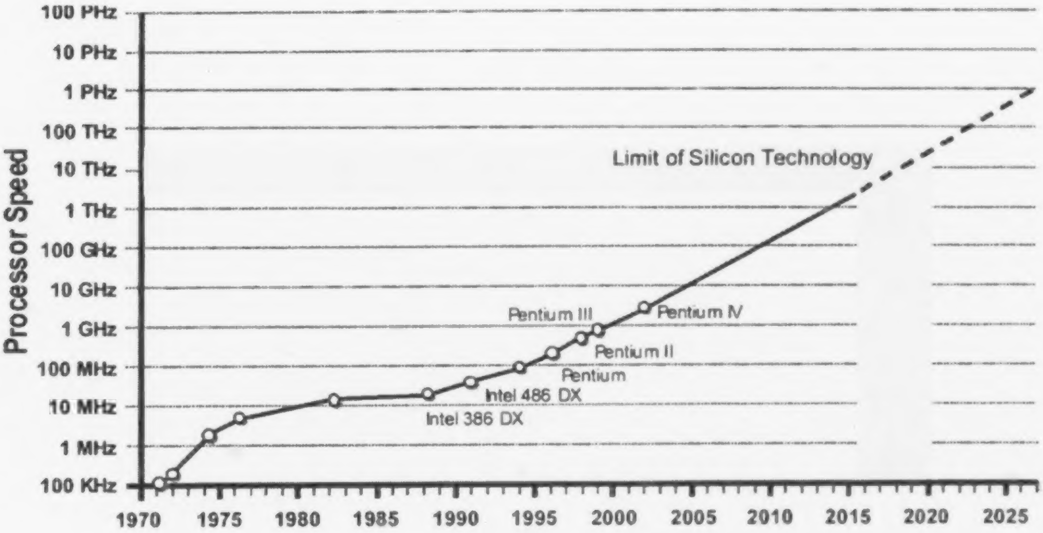

Figure 13: Processor Speed Trends[26]

Table 10: Core Technology Trends provides a list of core technologies for autonomous vehicles in terms of present-day capabilities; it also lists the requirements for such technologies to support autonomous vehicles by 2020. *Note: relevance to the aforementioned Enabling Technology Stream(s), which are outlined in Section 4, is indicated in bold for each Core Technology.*

Table 10: Core Technology Trends[27]

Core Technologies	Today	2020
Computing Power SSI, LSI, VLSI, Parallel Processing, Optical Computing, Protein-Based Computing **Relevant to: Intelligent Software, Sensing and Navigation**	MIPS	BIPS
Sensor Detection/Resolution Scanned/Staring arrays, Electronically Steered Antenna (ESA), Ring laser gyro (RLG), Fiber Optic Gyro (FOG) **Relevant to: Intelligent Software, Sensing and Navigation**	5 Km 0.5 mrad	50 Km 0.001 mrad
Algorithmic/Symbolic Methods Classical state space, Soft Computing, Fuzzy logic/Neural Nets, AI, Genetic Methods, Behaviour-based Techniques **Relevant to: Intelligent Software, Sensing, and Navigation**	Deterministic Multi loop system control	Adaptive Multi-dimensional Mission loop Optimization
Modeling and Simulation Super Computing, CAD, 3D Visualization, Multi-media Agent-Based Techniques	High Fidelity Integrated System	Virtual Reality Environment

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[26] Unmanned Aerial Vehicles Roadmap 2002-2007, Office of the Secretary of Defense, pg 42

[27] Applications, Concepts and Technologies for Future Tactical UAV's, RTO Lecture Series 224, pg9-4, Feb 2003

Core Technologies	Today	2020
Relevant to: Robotics, Dynamics and Mobility; Intelligent Software, Sensin, and Navigation; Control Systems	Constructs	
Communication/Information Distribution Internet Infrastructure, search Engines, Data/Info Extraction **Relevant to: Communications**	Massively High Integrated Systems Constructs	Network-Centric Multi-Media Information
Navigation Accuracy Autonomous Inertial Navigators, Satellite Navigation, Digital Terrain Mapping, 4-D Navigation **Relevant to: Intelligent Software, Sensing and Navigation**	100 m/h	1 – 10 m/h <1m.
Flight path Trajectory Management Fly-by-Wire, Multi Variable Closed Control, Multi-Vehicle Distributed Cooperative Control, Formation Positioning **Relevant to: Control Systems**	Integrated Flight Mgmt with Human Operator Oversight	Missionized Configuration Tailoring
Vehicle Management Architecture Distributed processing, MEMS, Photonics, MIMo Instrumentation, Fault Tolerant/Reconfigurable Command Signaling, Health Monitoring-Diagnostics and Prognostics **Relevant to: Intelligent Software, Sensing and Navigation; Control Systems**	Automated Subsystem Control	Real-time Integrated Performance Optimization
Real Time On-Board Mission Functions Sensing, Digital Processing, Information Fusion, Artificial Intelligence, Knowledge-based systems **Relevant to: Intelligent Software, Sensing and Navigation**	Integrated Mission System Functionality	Self Situation Assessment Autonomous Mission Management
Airframe Integration Sensor/Control Configured Vehicle, High Agility Blended Wing Body, Smart/Morphing Structures, Virtual Prototyping. **Relevant to: Robotics, Dynamics, Mobility; Materials; Power/Energy Systems**	Human Performance Limits	Missionized Configuration Tailoring

In *Table 11: Anticipated Research Effort for Technology Areas*, the level of effort required in each of the technology areas has been tabled for each battlespace. A rating of High indicates that there are significant technological barriers, while a Low rating indicates that either as a result of the research already performed for manned vehicles, or because there is not as much need for new technology in that battlespace, little effort is required.

This is clearly a qualitative approach to the mapping of battlespace-specific research effort and enabling technology streams. This initial effort to quantify this mapping was performed by assessing the technology readiness of each of the technology areas in each of the spaces based upon the capabilities of existing systems. Further, the level of complexity of issues remaining were considered to derive the final rating. This initial rating is intended to provoke discussion and to provide a framework for an ongoing assessment of the technologies.

Table 11: Anticipated Research Effort for Technology Areas

REQUIRED RESEARCH EFFORT (LOW, MED, HIGH) Battlespace	Robotics, Dynamics and Mobility	Intelligent Software, Sensing & Navigation	Control Systems	Materials	Communications	Power and Energy Systems
Space	Low	High	High	Medium	High	High
Air	Medium	High	Medium	Medium	High	Medium
Ground	Medium	High	High	Medium	High	Medium
Marine	Low	High	Medium	Medium	High	Medium
Undersea	Medium	High	Medium	Medium	High	Medium
Cyber	Low	High	Low	Low	Low	Low
Interbody	High	High	High	High	Low	High

Vehicle Performance Optimization (i.e., performance metrics) has been mapped to the various battlespaces in Table 12: Performance Metric Versus Battlespace Requirements for Research (see next page). Once again, a rating of High indicates that there is significant research effort required for autonomous systems to have the specific performance attribute.

As in Table 4, the intent is to provide the reader with a qualitative view (the approach to the rating of the various technologies within each space was the same as above) of where the research challenges currently exist. Depending on the battlespace of interest, different optimization paths will be required; these paths will require different combinations of research focus.

Table 12: Performance Metric Versus Battlespace Requirements for Research

Vehicle Performance Optimization										
REQUIRED RESEARCH EFFORT (LOW, MED, HIGH) Battlespace	**Scale**	**Range & Endurance**	**Maintainability**	**Availability**	**Reliability**	**Survivability**	**Payload**	**Stealth**	**Cost**	**Autonomy**
Space	Medium	High	High	Low	High	High	Low	Low	High	High
Air	High	High	High	High	High	High	Medium	High	High	Medium
Ground	Medium	Medium	High	High	High	High	Medium	Medium	High	High
Marine	Low	Medium	High	High	High	High	Medium	Medium	High	Medium
Undersea	Medium	High	High	High	High	High	Medium	High	High	Medium
Cyber	Low	Low	Low	Low	Low	High	Low	High	High	Low
Interbody	Low	Low	High	High	High	High	Low	Low	High	High

In order to achieve autonomous vehicles, research into the following Enabling Technologies is required as shown in Table 13: Minimum Effort to Create Autonomous Vehicle in each Battlespace:

Table 13: Minimum Effort to Create Autonomous Vehicle in each Battlespace

Enabling Technology	Focus of Effort Required to Advance Existing Technology to Deployment Stage
Robotics, Dynamics, and Mobility	**USV:** Well-established; incremental level of effort required **UAV:** Well-established; incremental level of effort required **UGV:** Significant work required on wheels, tracks and or legs to overcome obstacles and allow navigation on steep inclines or declines **UMV:** Well-established; incremental level of effort required **UUV:** Well-established; incremental level of effort required **UCV:** Well-established; incremental level of effort required However, optical and wireless research is clearly required (new highways).
Intelligent S/W	**All Battlespaces:** Significant work to add behavioural adaptation and learning
Sensing	**USV:** Well-established; incremental level of effort required **UAV:** Object recognition when moving, target, and threat recognition required **UGV:** As per UAV plus obstacle recognition, path optimization/viability **UMV:** Object recognition when moving, target and threat recognition required **UUV:** Well-established, incremental level of effort required **UCV:** Network, Server, spoofing, target and threat recognition required
Navigation	**USV:** Significant issues surrounding precise location knowledge **UAV:** Well-established; incremental level of effort required **UGV:** Significant issues surrounding: holes in GPS coverage, obstacle avoidance, cluttered environments **UMV:** Well-established; incremental level of effort required **UUV:** Well-established; incremental level of effort required **UCV**: Significant issues beginning with mapping the Internet; Means to navigate through firewalls and other security devices; Finding well-hidden targets
Control Systems	**USV:** Well-established; incremental level of effort required **UAV:** Well-established; incremental level of effort required **UGV:** Issues surrounding mobility, balance, etc.; moderate effort required **UMV:** Well-established; incremental level of effort required **UUV:** Well-established; incremental level of effort required **UCV:** Significant effort required
Materials	All battlespaces – significant effort in nanotechnology required

Enabling Technology	Focus of Effort Required to Advance Existing Technology to Deployment Stage
	and underway
Communications (see note below)	**USV:** Well-established; incremental level of effort required **UAV:** Well-established; incremental level of effort required **UGV:** Moderate research into solutions for communications disruptions due to cluttered environment **UMV:** Well-established; incremental level of effort required **UUV:** Well-established; incremental level of effort required **UCV:** Moderate effort to secure packet transmission back to base
Power/Energy Systems	**USV:** Well-established; incremental level of effort required **UAV:** Well-established; incremental level of effort required; however, for small-scale, significant work is required **UGV:** Well-established; incremental level of effort required; however, for small-scale, significant work is required **UMV:** Well-established; incremental level of effort required; however, for small-scale, significant work is required **UUV:** Well-established; incremental level of effort required; however, for small-scale, significant work is required **UCV:** Dependent on network power

These must fulfill the design requirements of:

- Affordability
- Flexibility
- Availability
- Survivability and safety
- Efficacy and efficiency

5.1 Robotics, Dynamics and Mobility

Mobility is defined as the ability of a UXV to traverse from point A to point B in a cluttered environment avoiding damage to itself while arriving at point B in a timely fashion. A high degree of mobility reduces the requirement for the fidelity of the perception task, supports timely arrival at position when carrying out a mission (required for covert operations, as these missions often involve taking the most awkward and indirect route to the objective) minimizes the risk of the vehicle entering a situation where it is unable to get to the destination.[28]

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[28] Technology Development for Army Unmanned Vehicles (2002), pg 76

5.1.1 Robotics, Dynamics and Mobility Issues for Space

Motion, either to change location or to maintain station, is currently dependent upon propellant brought with the vehicle on launch. This resource is used up with every move. Moves are currently necessary to align the solar cells, minimize cross section during meteorite storms and relocate orbital locations. Some means to replenish this propellant or a new mobility mechanism (i.e., solar sails) is necessary for vehicles that will have high mobility and long duration in space. Re-entrant vehicles which can be collected at a high altitude or that have the ability to fly back to earth without burning up would also allow such platforms to have significantly more use.

According to NASA[29] the high-priority in-space propulsion technologies include:

Aerocapture: Using a planet's atmosphere to slow a spacecraft – vehicle built for aerocapture can slip into orbit in one pass through an atmosphere. There is o need for on-board propulsion, so this saves mass and permits use of a smaller, less expensive launcher. This technique gets a vehicle to a destination quickly, hastening start-up of science operations;

Next Generation Electric Propulsion: Improve the performance of this technology, from ion engines to fission propulsion drives – high-throughput, lightweight and more powerful ion engines, for example, enable a host of future space missions, including a Europa Lander, a Saturn Ring Observer, a Neptune Orbiter and a Venus Surface Sample Return probe; and

Solar Sails: Strong, lightweight composite materials fashioned into a large sail. Requiring no fuel, a solar sail relies on the steady push of photons from the Sun. A major challenge is how best to unfurl a thin sail in space, then control its direction. Sail propulsion is seen as the way to launch an interstellar precursor mission in the next decade.

5.1.2 Robotics, Dynamics and Mobility Issues for Air

Air vehicles have a multitude of sizes, depending on the mission. These vehicles range in size from vehicles as large as manned airplanes to model size (six-foot wingspan) to extremely small (less than one foot across). The dynamics and mobility of the model to large size vehicles are well understood as they pose the same problem for manned vehicles. The smaller the vehicle, the less the physics behind flight stability is understood. Significant research is needed in order to understand flight with small Reynolds numbers, as well as the dynamics of insect flight. As these vehicles approach insect size, there is a requirement to develop new actuators and sensors. Current efforts including piezoelectric material that can be made to move in a pattern similar to insect wings to provide propulsion using the same principles as insect flight.

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[29] http://www.space.com/businesstechnology/technology/advanced_propulsion_020522-1.html

The Darpa SSPS Program[30] is currently being carried out through efforts to create new systems for propulsion, such as the following:

The MIT gas turbine laboratory is developing a rocket engine built with MEMS technology from multiple layers of etched silicon bonded together. The engine will use waste heat to operate turbo pumps for ethanol fuel and LOX. See http://web.mit.edu/aeroastro/www/labs/GTL/research/micro/micro.html.

Micro Craft is developing a Nitrous Oxide/Propane rocket. A catalyst bed will be used to decompose the nitrous oxide, which will then burn with the propane. The rocket will combine safety with high ISP.

The MIT gas turbine laboratory is developing a MEMS-based micro turbojet. This jet will have a single radial compressor stage and a single radial turbine stage and will use propane as its fuel. See http://web.mit.edu/aeroastro/www/labs/GTL/research/micro/micro.html.

CFD Research and Development is developing an Air Turbo Rocket. This is an engine that uses a solid fuel gas generator to drive a compressor, then burns the remaining fuel with air to produce thrust. See http://www.cfdrc.com/datab/Applications/atr/atr.html for more details.

General Electric Corporate Research and Development is developing a miniature air-breathing pulse detonation engine that will burn JP8 – the standard fuel of the US military. This system will eventually use a monolithic manufacturing technique to produce simple, inexpensive engines.

D-STAR Engineering is developing an innovative miniature turbine engine that will have very high thrust-to-weight and will be fuel-efficient. This engine will burn JP8. See www.dstarengineering.com.

RCV Engines is developing a twin-opposed piston, crankless version of their internal combustion engine with a rotating cylinder valve. This engine will have a high power density. See http://www.rcvengines.com.

5.1.3 Robotics, Dynamics and Mobility Issues for Ground

The mobility platform is highly application-dependent. Platforms for different mission applications will have to be designed based on differences in the mission requirements.[31] Currently there are a number of options for mobility including:

- Legged walking machines (2, 4 and 6 legs)*
- Tracked Vehicles

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[30] http://www.darpa.mil/tto/ssps/SSPS_Information.DOC

[31] Technology Development for Army Unmanned Vehicles (2002), pg 5

- Wheeled vehicle (2, 4, 6 and 8)
- Slithering (Snake-like)
- Crawling (Inchworm style)

***A sample of the Centres of Research for walking and ground vehicle mobility**

Japan
Dr. Osamu Matsumoto, Mechanical Engineering Lab., AIST, MITI (Biped type leg-wheeled robot)
Prof. Shuji Hashimoto, Waseda University, Tokyo (WABIAN)
Prof. Dr. Hiroshi KIMURA, Univ. of Electro-Communications, Tokyo (Collie II, Patrush, T-Hex)
Shuuji Kajita, Mechanical Engineering Laboratory (MEL), Tsukuba(Meltran II
Prof. Kenzo Nonami, Chiba University, Chiba (COMET-II)
Prof. Dr. A. Nishi, Miyazaki University (Ninjya)
Ahmet ONAT, Kyoto University, Kyoto, Japan (Gokiburi)
Kan Yoneda, Tokyo Institute of Technology (see AQUAROBO 1, ParaWalker, TITAN IV, TITAN VI, TITAN VIII, YANBO
Tomoaki YANO, Mechanical Engineering Laborator, Tsukuba (Wall Climbing Robot With Scanning-Type Suction Cups II)
Fuminori Yamasaki, Japan Science and Technology Corp.(PINO)
Europe
CLAWAR - Climbing and Walking Robots (http://www.clawar.com/)
GI-FA 4.3 Working-Group Walking and Climbing Robots
http://wwwipr.ira.uka.de/~germ_rob/
DFG-Program Autonomous Walking
http://www.fzi.de/ids/dfg_schwerpunkt_laufen/start_page.html
Canada
Prof. Dr. Martin Buehler, McGill University (see ARL Scout I, ARL Scout II, ARL Monopod II, RHex)
Dylan Horvath, University Waterloo (see AMWM)
Colin MacKenzie, Silicon R&D (see SYMAPOD)
Guillaume Lambert, École de Technologie supérieure, Québec, (see Hydraumas III
Colin MacKenzie, Silicon R&D (see Twitchy)
SAE Robotique, École Polytechnique de Montréal,Montréal, Quebec see Alexis)
Karl Williams, Waterloo, Ontario (see LIMA 1, Insectronic)
USA
Joseph Ayers, Northeastern University, Nahant, MA (Boadicea)
Mike Binnard, Center for Design Research Stanford (Boadicea)
Dr. John Bares, Carnegie Mellon University Pittsburgh (DanteII)
Skip Carter, Taygeta Scientific Inc. Monterey (Roboty)
Wendell H. Chun, Lockheed Martin Denver (Walking Beam)
Prof. Fred Delcomyn, University of Illinois (Hexapod Mark I)
John Dick, Applied Motion, Inc. (SpringWalker)
Peter Dilworth, MIT (Troody)
Dr. Jan Henri Cocatre-Zilgien (Autpod)

Kevin Dowling, Carnegie Mellon University Pittsburgh (Daedalus)
Roderic Grupen, University of Massachusetts (Thing)
John Jameson, Jameson Robotic San Carlos (WalkingGyroscape)
Abhinand Lath, Univeristy of Michigan (Hydrapod)
M. Anthony Lewis, Iguana Robotics, Inc.(Geo-II and Rodney)
Tad McGeer, The Insitute Group, Bingen (Dynamite Series)
David Peins, Manalapan High School, Englishtown (Ambassador)
Jerry Pratt, Massachusetts Institute of Technology (Spring Flamingo)
Ivan Richardson, 488 Blair 20 Eugene, Oregon (Richardson Bug)
Dr. Roger Quinn, Case Western Reserve University Cleveland (CWRU Robot II)
Andy Ruina, TAM, CORNELL University, Ithaca, NY
P. Douglas Reeder, Ohio State University, Columbus Triped)
Andy Ruina, TAM, CORNELL University, Ithaca, NY
Dr. Reid Simmons, Carnegie Mellon University Pittsburgh (Ambler)
Gaurav S. Sukhatme, University of Southern California Los Angeles (MENO \ ref meno)
Prof. Dr. K. J. Waldron, The Ohio State Univiversity Columbus (ASV)
Mark Yim, Stanford University, California (Polypod)
Dr. Yuan F. Zheng, Ohio State University Columbus (Curbi)

Mission requirements range from traversing terrain with heavy equipment at a high speed, to exploring the rubble resulting from a bomb blast looking for victims, survivors or intelligences, to following duct work and other internal building path ways to investigate and eavesdrop.

Issues around balance and recovery from being off-balance require dynamic control systems. Although numerous algorithms exist for walking, improvements are required for traversing cluttered and uneven terrain.

It is necessary to develop the ability to identify issues in the surrounding terrain that could lead to a loss of balance and to develop strategies for overcoming potential loss of balance. Also of prime importance is developing an ability to accommodate for the impact of weather on the algorithms for balance and understanding terrain.

Additional considerations are:

- Shock constraints for collision, rollover and blasts
- Vibration
- Road following
- Intersection detection
- Traffic avoidance
- Understanding signals (signs, lights, etc.)

5.1.4 State-of-the-art in Leg mobility – an example from MIT[32]

Mission Goal:

Troody is an exploration of the application of walking robot technology to dinosaur robots. The goal of the robot is to stand up, balance and walk around. This technology will have useful applications where there is interest in dinosaurs, the study of biomechanical locomotion and robotics in general.

Hardware Design:

Troody is a two-legged robot, modeled roughly on the Late Cretaceous dinosaur Troodon. It has on-board batteries and computers, and can operate without external wires for control or power. The body design of therapod dinosaurs is a very good one to copy for an agile two-legged robot, and the tail can help with balance and turning. There are 16 degrees of freedom:

- Tail up/down swing
- Tail left/right swing
- L leg abduct/adduct
- R leg abduct/adduct
- L leg twist about vertical axis
- R leg twist about vertical axis
- L leg hip
- R leg hip
- L leg knee
- R leg knee
- L leg ankle
- R leg ankle
- L outside toe up/down
- L inside toe up/down
- R outside toe up/down
- R inside toe up/down

Robot specifications:

- weight: 4.5 kg. (10 lbs.)
- height: about 45 cm (about 18 inches) at the hips when standing
- length: about 1.3 meters (about 4 feet) from tip of snout to end of tail
- batteries: 24V x 1.2 Ah NiMH fast-charge batteries, good for approximately 30 minutes of operation per charge
- motors: six standard DC-brushed type motors for main leg power motors, 8 "lobitomized" (control electronics removed, motor and gear heads, only) futaba servo motors for internal hip and toe motors and tail motors
- computer: one TMS320c30 DSP for main processor. The robot has several megabytes of DRAM, as well as about 64kX32bits of FLASH memory, used for program and data store for tetherless operation.

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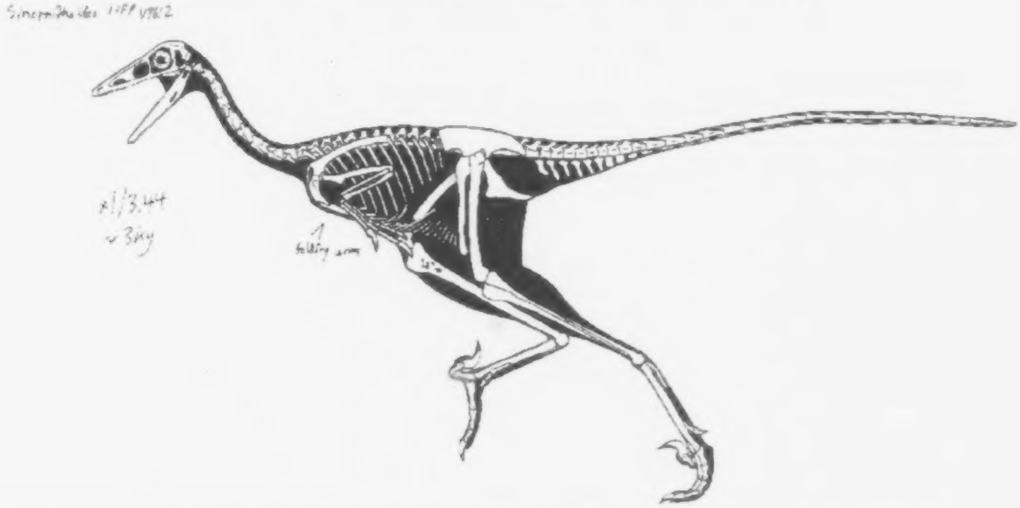
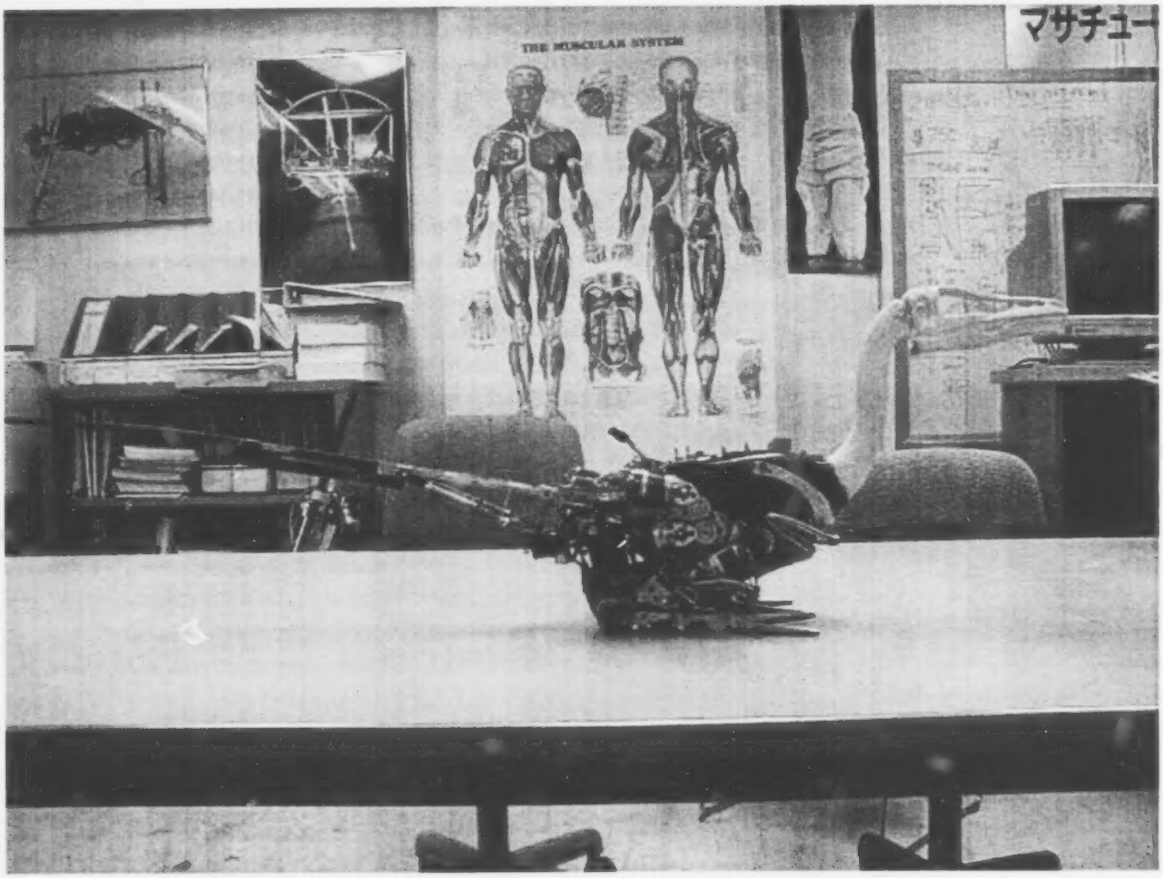
[32] http://www.ai.mit.edu/projects/leglab/robots/robots.html, 2001

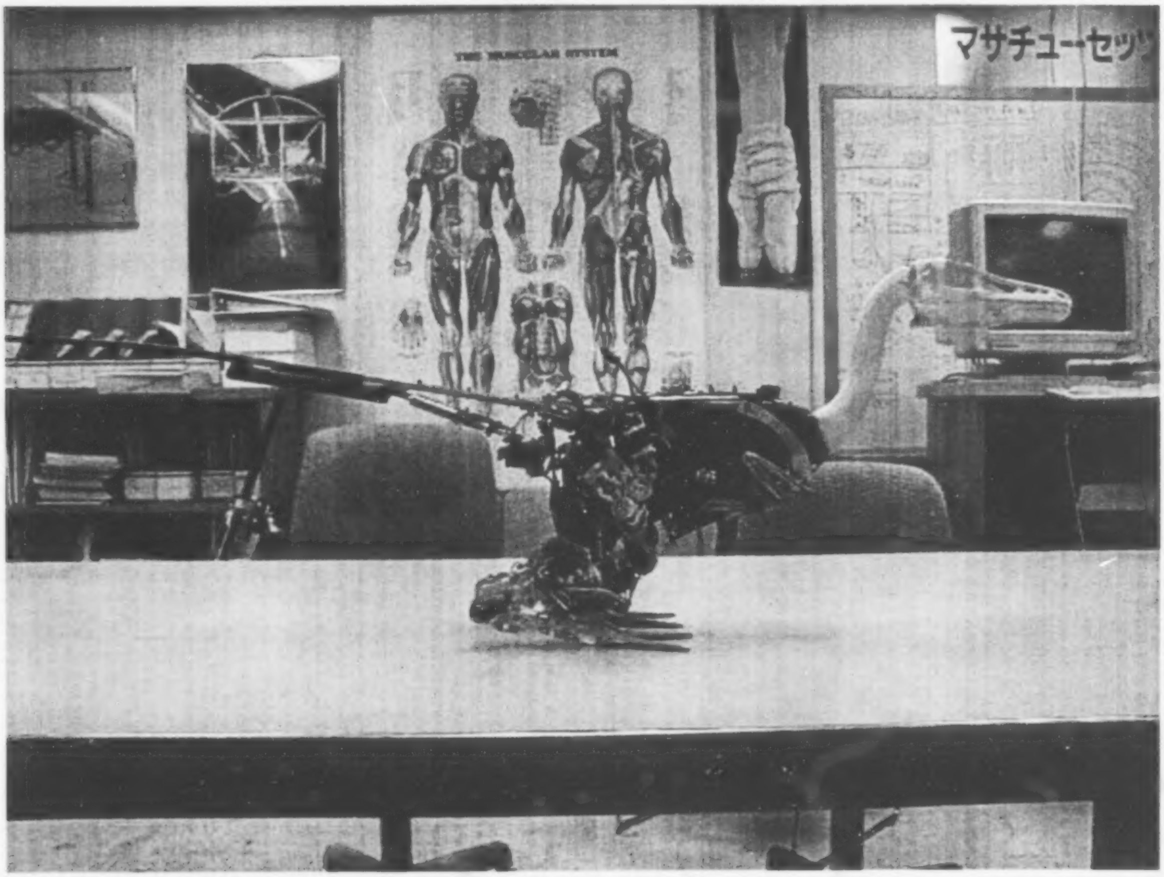
- power electronics: There are four 3x5 inch cards that each control four motors using high-current Fet H-bridge hysteresis mode controllers. Each controller operates with a current control inner loop, a voltage control loop around that and a force feedback control loop around the outside. All feedback control occurs in analog hardware. These motor driver cards are given desired torque represented as a voltage level, by the DSP. Each card is capable of generating up to 24V @ 10A for short periods, per channel without the use of heatsinks or other cooling components.
- external power input: The robot can be run off a single 24V external line. The same line can be used to charge the batteries at 30V.
- computer interface: The robot can operate stand alone (autonomous operation, guided by on-board sensor input), by joystick remote control or by a host computer via a serial line (the host is only used to send high-level commands or to download run time telemetry for graphical display). We use a PC running Windows as the remote host.
- walking control system: The robot uses a control system called "PQ-control"; more information will be forthcoming once patent issues have been taken care of.

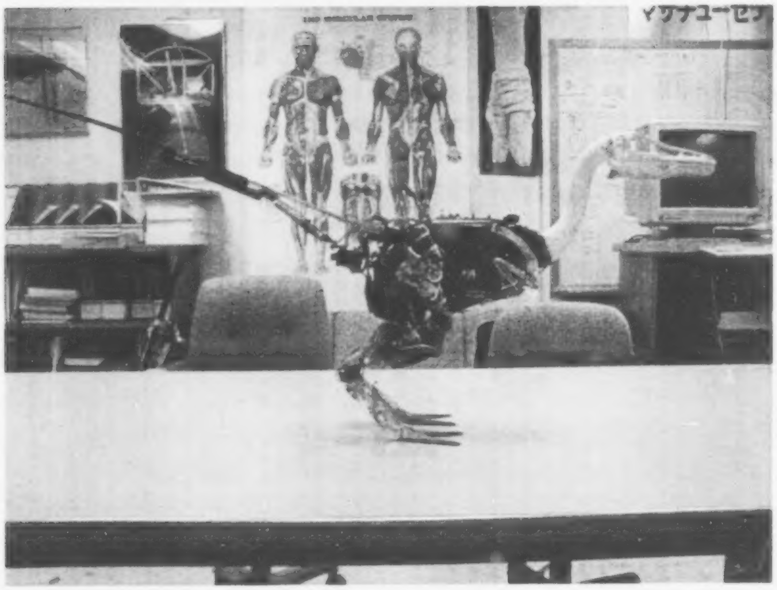
This is a plan view of a Sinornithoides, or Troodon dinosaur based on recent archeological work. (this image was created by Gregory S. Paul, 1997)



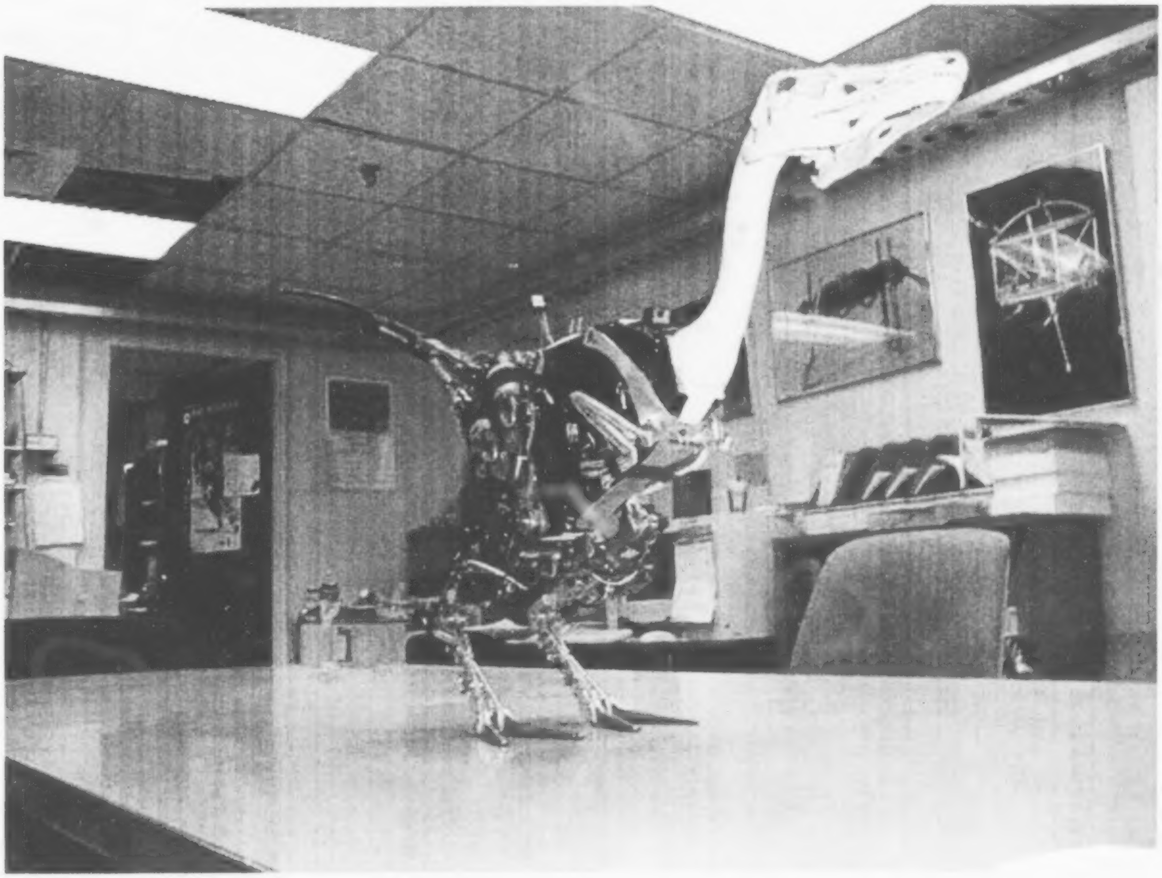
Below are a series of images showing the robot sitting, sitting up and standing. All of these operations took place under fully autonomous mode, using internal batteries for power, and a hand-held IR remote to send the command to stand.

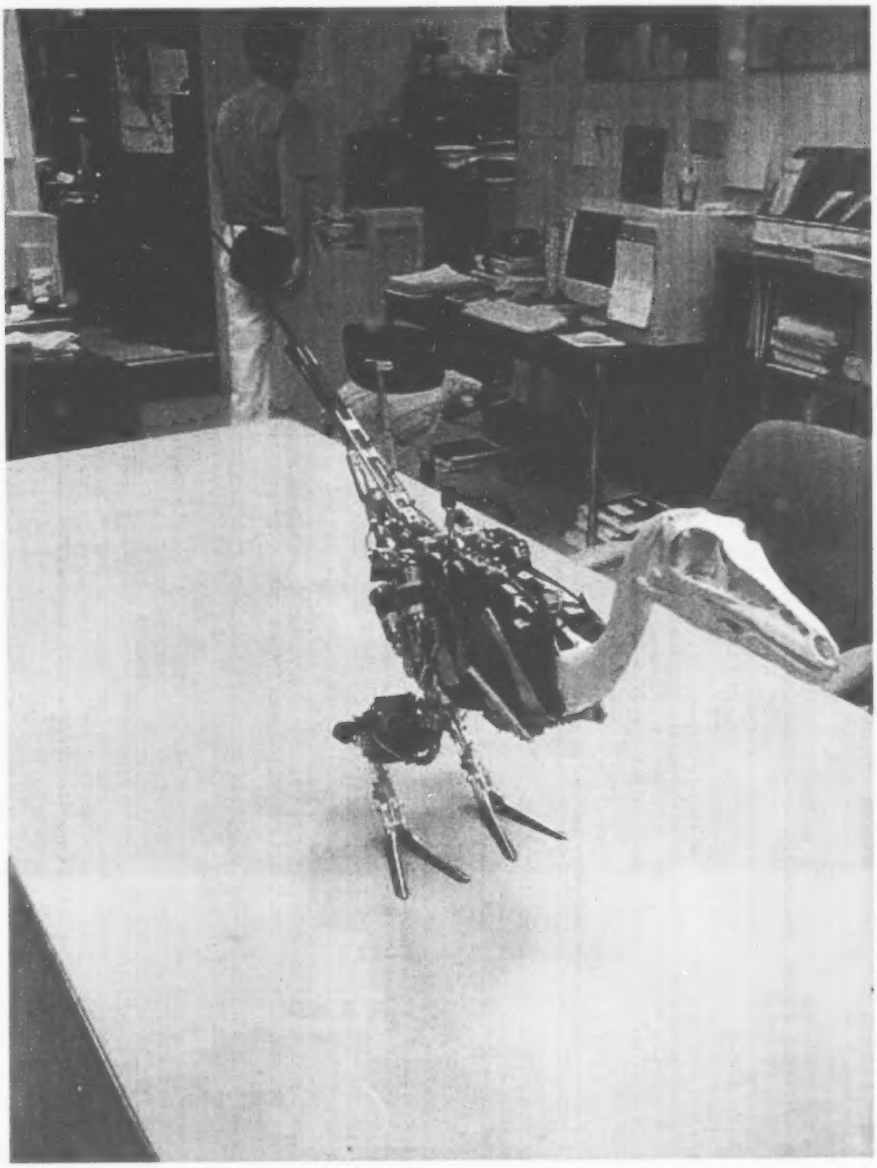

THE MUSCULAR SYSTEM
マサチュー


THE MUSCULAR SYSTEM
マサチューセッツ



Here are some further images:





Troodon status report:
28 Sept 1998 – All hardware and electronics are assembled, and have been working with no major failures for about seven months. The robot is currently being programmed. It can stand up autonomously from a sitting position without outside assistance (most of the time!) and can balance despite outside disturbances (we ran it outside with 15-20 mph wind gusts and it kept its balance!).

5.1.5 Robotics, Dynamics and Mobility Issues for Marine

We were unable to identify unique robotics, dynamics and mobility issues during this study and recommend further efforts to evaluate this area.

5.1.6 Robotics, Dynamics and Mobility Issues for Underwater

Existing efforts by the US Navy are based around miniaturized submarines using many of the same technologies for mobility as are currently used in one- and two-man subs. Major issues surrounding the ability to travel under water include having accurate knowledge of location, maintaining motionless in currents and maintaining buoyancy. New propulsion techniques suitable for smaller underwater crafts include propellant, as used in manned sleds, and fish-like motions need to be developed.

5.1.7 Robotics, Dynamics and Mobility Issues for Cybots

We were unable to identify unique robotics, dynamics and mobility issues during this study and recommend further efforts to evaluate this area.

5.2 Intelligent Software, Sensing and Navigation

These involve planning, perception, behaviour and skills, learning and adaptation, health maintenance and human machine interactions.

Core capabilities for Intelligent Control architectures[33] are: World modeling and mapping, task definition and decomposition, multi-vehicle coordination and cooperation, symbolic planning, geometric planning, tactical behaviours and contingency handling. Achieving fully autonomous UXV navigation will require the integration of perception, path planning, communications and various navigation techniques. This integration is the largest technological gap in autonomous navigation.[34]

Examples of Emerging Sensor Technologies

Multispectral/hyperspectral imagery (MSI/HIS) to form a literal image of a target with the ability to extract subtler information[35] – multispectral refers to fusing tens of spectral bands together to compose an image while hyperspectral refers to fusing hundreds of spectral bands into a single image.

Side Aperture RADAR phase data enhancements for detecting changes in terrain.

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[33] Joint Robotics Program Master Plan FY 2002, OUSD (AT&L) S&ST/LAND Warfare, Washington DC, Section 7.5, pg. 112

[34] Technology Development for Army Unmanned Ground Vehicles (2002), pg 4

[35] Unmanned Aerial Vehicles Roadmap 2002-2007, Office of the Secretary of Defense, pg 90

UHF/VHF Foliage Penetration (FOPEN). Dual-band radar, using VHF wavelengths to cue a UHF radar for more precise target identification.

Light Detection and Ranging (LIDAR) – combine several for-and-aft images to enhance target identification. Also using precision short laser pulses and evaluating the first photons to allow return penetration through various obscurations.

Enabling Technologies for Sensors

HDTV video formats represent a fundamental shift in video technology from an analog interlaced video stream to high-resolution digital image format. This technology should result in enhanced data quality, reductions in bandwidth requirements and the ability to reliably feed downstream algorithms (perception) that use this data with high content rich data.

Focal Plane Array Technologies to enable a reduction in the size and power requirements of video sensors for use on small UXVs. These arrays will become multi-spectral, adding to their utility.

Increasing sensor autonomy (intelligent sensors) enabling much of the preprocessing to occur at the sensor, and only the appropriate information is then sent to the upstream components. Research efforts focussed on integrating sensor data and performing preprocessing are active around the world. DRDC has a number of projects in this area. For example, video subsystems are provided several target profiles of interest and then these subsystems automatically scan the area and analyze the image for clues that targets of interest may exist in the image. Only at that point is the image passed to the next level of software or sent back to the central command.

Sensor fusions to link multiple sensors and then preprocess the combined input into an amalgamated data product for upstream processing.

Current Efforts in MEMS Sensors and Actuators (a sampling)

http://transducers.stanford.edu/stl/Projects.html
http://www.engin.umich.edu/facility/cnct/index.html
http://www.its.caltech.edu/~pinelab/old_webpage/pinelab.htm
http://www.ece.cmu.edu/~mems/
http://mems.cwru.edu/Pages/knowus.html
http://mems.nist.gov/
NIST MicroFluidics Project
NIST MicroHotplate Gas Sensors Project
MOSIS MEMS Website
Cronos MEMS Website
The MEMS Exchange
George Washington University MEMS Institute
University of Maryland Center for MicroEngineering

Georgia Tech MEMS Home Page
Georgetown Advanced Electronics Laboratory
Trimmer/Stroud Database
Sandia National Labs MEMS Website
Berkeley Sensor and Actuator Center
ETH Physical Electronics Laboratory
Case Western Reserve University MEMS Website
The Semiconductor Subway
MEMS Alliance
MEMS Guide

Required new sensors in the area of[36]:

1. Acoustic sensors
2. Electronic surveillance payloads
3. Chemical and biological detectors
4. Mine detection sensors (land and sea)

5.2.1 Intelligent Software, Sensing and Navigation Issues for Space

We were unable to identify unique Intelligent Software, Sensing and Navigation issues during this study and recommend further efforts to evaluate this area.

5.2.2 Intelligent Software, Sensing and Navigation Issues for Air

Intelligent sensors (sensors that have a microprocessor collocated where some of the sensor signal preprocessing is performed before being made available to the system using the data) represent the most important part of the UAV payload, as they are essential to tactical situational assessment and are also partly replacing the pilot's eyes. Independently from the mission, sensors represent a major integration issue due to their unique role.[37]

5.2.3 Intelligent Software, Sensing and Navigation Issues for Ground

Key abilities for UGVs include obstacle avoidance, terrain characterization and classification, fusion of data from multiple classifiers, route planning, safe driving, tactical behaviour soldier-vehicle interactions. Techniques and sensors for dealing with water obstacles, negative obstacles (ditches), mud or swampy regions, slopes, etc.

5.2.4 Intelligent Software, Sensing and Navigation Issues for Marine

There is a requirement for software to adapt to the following domain-specific problems:
Compensation for drift – similar to aircraft flight systems
Long brake periods compared to ground (inertia)

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[36] Applications, Concepts and Technologies for Future Tactical UAVs pg 2-1
[37] Integrated Mission System Concepts and Technologies for Future Unmanned Combat Applications pg 83

5.2.5 Intelligent Software, Sensing and Navigation Issues for Underwater

There are a number of issues surrounding the development of intelligent software for this battlespace. These include having an accurate knowledge of where the vehicle is since GPS does not work under water. Thus there is either a reliance on accurate maps of the terrain, placement/reliance on location beacons or incorporation of sensors to detect the GPS signal or behaviour which brings the UUV to the surface periodically to verify the world model. Without accurate knowledge of the vehicle's position, there is a requirement to compensate for drift due to currents, etc. The major problem developing intelligent software will be in developing behavioural capability for these devices.

5.2.6 Intelligent Software, Sensing and Navigation Issues for Cyberbots

We were unable to identify unique Intelligent Software, Sensing and Navigation issues during this study and recommend further efforts to evaluate this area.

5.3 Control Systems

The following issues remain unknown in the design of control systems, yet will have significant impact on the design of such systems: robotic span of control, determination of the number of autonomous robotic assets that can be effectively commanded by a single operator, the networking of the soldier/robot system to other manned and unmanned assets for operations.

As with many complex systems requiring advanced control, important areas of research, identified by reviewing current activities underway at various universities and papers presented at recent conferences on control systems, include:

- Adaptive control systems
- Fault tolerant control
- Failure recovery
- Cerebellar control
- Neural network control
- Predictive control modeling
- Particle physics control
- Rule-based control
- Decentralized control
- Inertia decoupling
- Economic model

The UXV research will take control system research to a very high level of sophistication.

Efforts into control systems hinge around two main activities:

- Provision of a smooth conflict-free movement in a known space;
- Engineering graceful machine dynamics when the UXVs approach objects and, possibly, contact them.

This is extremely significant when dealing with humans in the workspace. As a result, much of the effort revolves around mechanisms to incorporate the existence of detected objects into the control algorithm. For example, if an object is detected in or near a planned path, the UXV must modify the path and its motion according to certain rules, learned behaviour or models. This will reduce the likelihood of collision, or interference, with the other object. Models for incorporating objects include allocating a value to the distance between the UXV and the object and using this value as a cost associated to moving towards the object. Knowledge-based decisions for the size, texture, etc. of the object, and adaptive learning models, are employed to deal with such objects.

5.4 Materials

Small UXVs will need to be lightweight and protected from damage during transportation and while in operation. Advances in nanotechnology and composite material manufacturing will result in new abilities to integrate sensors into the material, improve stealth and reduce weight while increasing strength.

The US National Nanotechnology Initiative focuses on research efforts to develop a revolutionary multi-disciplinary balanced portfolio containing "sustaining" research and development activities. There are three task areas under Nanotechnology: 1) Materials, 2) Power and 3) Instrumentation. The technologies to be developed under these tasks consist of: Self-assembly Molecularly Engineered Polymers and Organic Materials, Nanoenergy Storage Concepts, Lithium Battery NanoAnodes, Quantum Entanglement, Nanoarrays Visualization and Silicon Carbide Nanotubes for Sensors and Electronics. This effort is further elaborated on in the following[38]:

Materials:
The emphasis of this task is to utilize novel polymer architectures and molecular self-assembly to develop new materials with novel structural, electronic or optical properties. The following aspects of supramolecular chemistry will be explored to develop advanced materials for propulsion and power applications:

- Self-Assembled Materials: Certain chemical groups, e.g., hydroxyl groups or strong dipoles, on a polymer or organic molecule can produce strong non-bonded interactions between molecules or polymer chains. These interactions can lead to an ordering or assembly of molecules very much like sticks tightly packed in a bundle. Self-assembled materials might offer unique mechanical properties since these non-bonded interactions will act as "soft" cross-links between polymer chains. For most cross-linked polymers, there is usually a trade-off between strength and toughness. However, it may be possible to exploit the "soft" cross-links in self-assembled materials to achieve both high strength and high toughness. Self-assembled materials can also be used as a template upon which to attach groups with special electrical or photonic properties. This templating would serve to align the electro-active or photonic groups to maximize their performance. This type of self-assembled material would have potential applications in sensors, electrode materials and polymer electrolytes for batteries and proton exchange membranes for fuel cells.

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[38] NASA Glenn Research Center

- Dendrimers and Hyper-branched Polymers: Dendrimers are spherical, highly symmetrical branched macromolecules. These compounds have been shown to have interesting melt behaviour that may make them useful as additives to improve the processability of high temperature polymers and polymer matrix composites. However, their potential applications extend beyond the limits of structural materials. Recent developments have shown that it is possible to synthesize dendrimers that have different chemical groups on their exterior than they have in the core. These multifunctional dendrimers could find potential applications in sensors and energy storage materials. For example, a dendrimer could be synthesized so that it has a fluorescent core that could be quenched by electron transfer and an outer shell that contained electron donating groups that could quench the core. The extent of this electron transfer would be controlled or mediated by the polarity of the dendrimer's environent, and the intensity of the fluorescence from the dendrimer core would change (increase or decrease) depending upon the environment.

Power:

- NanoEnergy Storage Concepts

The object of this task is to asses the "practical" technical feasibility of utilizing nanotubes for revolutionary energy storage concepts: (a) hydrogen storage, (2) hydrogen/air battery. The advancement of nanotechnologies will require a long-term, high-risk approach, with a potential payoff expected to be extremely large. The revolutionary development approach proposed here embodies the strategy of investing at a relatively modest level for a "proof of concept." The carbon nanotubes will be investigated to determine potential as a hydrogen storage system and a design of a hydrogen/air battery. Recent reports in the literature claim that it is possible to store hydrogen in carbon nanotubes. This task is to verify those claims as well as look into doping the nanotubes to determine the effects of modifying the carbon chemical structure. If storage capability does indeed exist,

- Does it show significant improvement to current hydrogen storage methods?
- Can it be incorporated into a viable system? How many charge/discharge cycles are possible?

- Is the surrounding gas (hydrogen) pressure a contributing factor to the rate of hydrogen release/storage?

In addition, this task will investigate the use of carbon nanotubes to build a hydrogen/air battery. The bipolar plates will be built out of a nanotube composite and will store hydrogen. The fuel cell will continue to run until hydrogen is exhausted from the plates. It will need time to be recharged, but no external supporting system is needed, more like a battery. It offers the potential to be an extremely lightweight system.

Lithium Battery Nanotube Anodes
The objective of this task is to produce and evaluate chemical vapor-deposited carbon nanotube anodes for thin film lithium ion batteries. In contrast to carbon black, directed structured nanotubes and nanofibers offer a superior intercalation media for Li ion batteries. Carbon lamellas in carbon blacks are circumferentially oriented and block much of the particle interior, rendering much of the matrix useless as intercalation material. In contrast, nanofibers can be grown so as to provide 100% accessibility of the entire carbon structure to intercalation. Moreover, this high accessibility also confers a high mobility to ion exchange processes, a fundamental for dynamic response of batteries based on intercalation.

Nanotubes will be grown via chemical vapor deposition methods using high-temperature furnaces. In this process, the catalyst is prepared prior to growth by standard techniques. Through control of the process temperature and reactive gas-phase species, nanotubes of different lengths and orientations can be grown. Catalyst preparation methods include a) in-situ preparation by decomposition of a metal salt, b) precipitated colloids or c) preformed nanoparticles synthesized by aerosol methods. Each of these techniques offers advantages for control of particle composition and size. Moreover, each is compatible with a variety of substrate materials suitable as battery electrode material. Upon preparation and/or deposition of the catalyst on the substrate, nanotubes may be grown by CVD. Control of the gas temperature is used to enable nanotube growth while minimizing pyrolytic decomposition and subsequent amorphous carbon deposition. Reactant gases such as CO or C2H2 will be used to aid in selection of the graphitic content of the nanotubes. The as-deposited nanotube morphologies will be analyzed using high resolution SEM, TEM and atomic force microscopies. The Li capacity for the different nanotubes will then be compared by electrochemical analysis of battery half-cells. Finally, the nanotube films will be incorporated into a prototype thin film lithium battery that utilizes a hybrid lithium electrolyte and lithium cobaltate cathode. These batteries will be characterized in terms of their overall capacity, rate of discharge and cyclability.

- **Instrumentation:**

Quantum Entanglement for Sensing Systems and Nanoscale (NEMS) Transceivers
The objective of this research is to verify and advance revolutionary experiments that have demonstrated a "non-local" quantum relationship between elementary particles, also known as Quantum Entanglement (QE), at a distance (>10km). The experiments used quantum mechanically entangled particles (photons, electrons, neutrons, etc.) and have

demonstrated effects that have the potential of revolutionizing current sensing and communication methodologies. This technology could solve the ongoing problem of how to communicate with, or otherwise extract information from, a Nano-scale Electromechanical Systems (NEMS) device. This work does not simply strive to miniaturize existing devices, but instead leverage the intrinsic scale of elementary particles.

Photonic Interrogation and Control of NanoArrays

The principle focus of this study is to develop a new photonic technology which delivers optical energy to nano-swarms or a multitude of nano-objects and/or nanodevices via a device-local holographic grating. The grating will decode photonic instructions by redirecting the photons to specific regions of the nano-swarm. The energy will interact with each nano-device by generating heat, initiating or terminating a chemical reaction, controlling an opto-electrical process, and/or through photon pressure to generate a mechanical force. This induced force will selectively and intelligently control the activity of the nano-devices. The grating will also store the device "genetic code." The grating can be constructed optically or chemically, but will be interrogated and energized photonically.

Early efforts will employ modeling and simulation at optical frequencies and micro scales, and will support development of coherent x-ray imaging technology for nano-scales. Artificial neural networks will be used for fast array image processing and comparison with computational models.

Development of Silicon Carbide Nanotubes (SiCNT) for Sensors and Electronics

The objective of this task is to evaluate multiple approaches to synthesize and characterize the highest performing SiCNTs for high temperature and high radiation conditions. It is also to develop sophisticated modeling and simulation technologies that will facilitate the research and development of various chemical techniques for SiC-based nanotube (SiCNT) fabrication and to further expedite the design and prototyping of more complicated assemblies and devices made from SiCNTs.

Multiple synthetic approaches are planned which parallel the direct CNT formation as well as an indirect approach involving derivatization of a CNT to a SiCNT. One indirect approach that may be envisioned to produce a SiCNT, which can be thought of as a chemical derivative of a CNT, starts with a CNT that is modified by chemically attaching different Silicon-containing functional groups to the CNT (functionalizing). This derivatized-CNT is then pyrolyzed in an appropriate environment to yield a SiCNT. A more direct approach would employ Chemical Vapor Deposition (CVD) using reduced partial-pressures of reactants and trace amounts of catalysts to directly obtain SiCNTs . This more direct fabrication attempt would rely on high temperature (2000°C) CVD using a catalytic (trace metal) substrate.

Once fabricated, the SiCNTs electrical and mechanical properties would be characterized and compared with theoretical SiCNT modeling results. The electrical properties include investigations into potential semiconductor properties that could be extended to higher (than CNT) temperatures. Electrical activity of SiCNTs could also be studied as a function of adsorbates, which could ultimately lead to applications such as nano-gas-sensors for harsh environments. Mechanical properties to be studied include tensile and compressive stress for structural components (e.g., actuators) and also their effect on SiCNT electrical properties. Knowledge gained from these fabrication results and empirical investigations can be incorporated into the models of the simulation environment to improve fidelity.

5.5 Communications

A problem exists with regard to wireless communications when operating the system in areas where the normal frequencies used for communications are used for other devices or are unavailable in that geographic area; or line of sight is not possible; and when there is a real threat of intercept and rebroadcast.

Near-term communications architectures will need to support:
Line of sight (LOS) capabilities with an ability to select the operational frequency based upon the mission parameters. Data rates to 250Mb/s and greater will be required.

Narrow band Beyond Line-of-Sight (NB-BLOS): Data rates below 1Mb/s supporting sensor data feeds back to a central command.

Wide-Band Beyond Line-of-Sight (WB-BLOS): Data rates above 1Mb/s providing Data relay services, hyperspectral image data, etc.

Increasing the processing capability of the on-board systems can reduce the bandwidth requirements by enabling the transmission of only relevant information along with a large amount of data fusion. With off-board processing, all data must be sent in a real time stream or selectively.

Fully autonomous collaborating systems will require, for example, a network-centric dynamic communications infrastructure to enable the mission-specific interactions between each individual system throughout network-centric operations. Network-centric operations are military operations that exploit state-of-the-art information and networking technology to integrate widely dispersed human decision makers, situation and targeting sensors, forces and weapons into a highly adaptive, comprehensive system to achieve unprecedented mission effectiveness.[39]

The dynamic nature of this communications network requires rethinking many of the details involved in the various layers of the networking infrastructure. The environment will involve high node mobility, limited transmission opportunities and rapid link characteristics. These types of networks will require the following capabilities:[40]

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[39] Integrated Mission System Concepts and Technologies for Future Unmanned Combat Applications pg.98
[40] Integrated Mission System Concepts and Technologies for Future Unmanned Combat Applications pg.98

- Self-organization and self-healing of both the topology and the grouping of the network nodes
- Network control of the route, location and traffic management
- State characterization
- Medium access control
- Link quality control

The goal is to enable a seamless communications architecture which can pass data between the aircraft and the control station through a variety of paths to ensure a robust system.

Emerging and Enabling Technologies include:

- Spread spectrum waveforms
- Intelligent high dynamic bandwidth network protocols
- Multi-band multimode radios
- Agile beam conformal antennas
- Smart skins
- Smart push/pull warrior decision aids and planning tools
- Network security

Further, to ensure interoperability between various systems, standards are required in the following areas:

- Message and data forms
- Communication protocols
- Electrical and mechanical interfaces
- Data link parameters
- Integrated logistic support tools /methodologies

5.6 Power/Energy Systems

As every component of the UXVs shrink in size there is a corresponding requirement to shrink the size of the power supply while increasing the available life of the power supply before refueling is required. Micro UXVs will require very high power/weight ratios to maximize the sensor load available while extending the endurance of the unit. UXVs have the following general requirements:

- Increased reliability
- Increased fuel efficiency
- High power-to-weight ratios

These requirements will be met with new lighter materials, new fuels, improvements in fuel cells, etc. As the scale of the UXV decreases, there is a requirement to develop smaller battery-based power systems. As the scale moves to the micro scale, new power systems will be required. Future-looking efforts for UXV propulsion should include the use of fuel cell, nuclear-based power schemes as well as MEMS technology (to reduce the weight of the engine, improve the efficiency and reduce the size) and new bio-chemical processes.

Emerging Propulsion Technologies include[41]:

- Beaming energy to the UXV for conversion to electricity using either microwaves or lasers thus eliminating the requirement to carry fuel onboard.
- Reciprocating Chemical Muscles: One example of a new bio/chemical power process based upon a chemical process similar to the ATP process in the human body that will allow systems to be fueled using sugar compounds that are converted to ATP which is then distributed to the individual sensor, actuator and processing unit that would convert the ATP required into energy.
- For short-burst high-power output, technologies include: Ramjet, scramjet, integrated rocket-ramjet, air-turbo rock and pulse detonation engines.
- Nuclear fuel engines for systems requiring operational endurance of greater than six months.

5.6.1 Power/Energy Issues for Space

Without re-entry vehicles, space vehicles are permanently located in the atmosphere and therefore are dependent on the ability to either create usable energy via solar cells or to have very long duration sources such as nuclear power. Battery life is a serious issue with such vehicles. The number of recharge cycles effectively defines the life expectancy of space vehicles today.

NASA Selects In-Space Propulsion Innovations for Research[42]

NASA has selected 15 industry, government and academic organizations to pursue 22 innovative propulsion technology research proposals that could revolutionize exploration and scientific study of the solar system.

Total value of the work to be done over a three-year period is approximately $20 million, with $9.6 million in fiscal year 2003; $10.2 million in fiscal year 2004; and $0.6 million in fiscal year 2005. The research will be conducted in five, in-space propulsion technology areas: aerocapture, advanced chemical propulsion, solar electric propulsion, space-based tether propulsion and solar sail technologies.

Each technology identified for development is part of the In-Space Propulsion (ISP) Program, managed in the Office of Space Sciences, NASA Headquarters. The awards are being made as part of the In-Space Propulsion Technologies "Cycle 2" amendment to

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[41] Unmanned Aerial Vehicles Roadmap 2002-2007, Office of the Secretary of Defense, pg 118

[42] http://www.nasa.gov/home/hqnews/2003/may/HQ_news_c03Q.html

NASA Research Announcement 02-OSS-01.

"We want to increase the frequency, speed and return on our missions and enable whole new missions that are impossible or impractical with today's propulsion technologies," said Dr. Colleen Hartman, director of the Solar System Exploration Division, NASA Headquarters.

"This round of selections further broadens NASA's investment portfolio for in-space propulsion technologies," said Paul Wercinski, ISP Program Executive, Office of Space Science, NASA Headquarters. "We are excited to see these technologies eventually fly on future science missions."

"Our goal is to develop technologies that will make deep-space exploration more practical, more affordable and more productive," said Les Johnson, In-Space Transportation manager at the NASA's Marshall Space Flight Center (MSFC), Huntsville, Ala.

Contract awards:

Aerocapture Technology:

Ball Aerospace, Boulder, Colo.
Lockheed Martin, Denver

Advanced Chemical Propulsion:

TRW Space & Electronics, Redondo Beach, Calif.

NASA Jet Propulsion Laboratory, Pasadena, Calif. (three awards)

VACCO Industries, Inc., El Monte, Calif.

Kilowatt Solar Electric Propulsion System:

NASA Glenn Research Center, Cleveland
Busek Co. Inc., Natick, Mass.

Momentum-eXchange/Electrodynamic Reboost (MXER) Tether Technology:

Tethers Unlimited, Inc., Lynnwood, Wash. (two awards)
Smithsonian Astrophysical Observatory, Cambridge, Mass.
Tennessee Technological University, Cookeville, Tenn.
Lockheed Martin, Denver (two awards)

Solar Sails:

NASA Langley Research Center, Hampton, Va. (two awards)
NASA Jet Propulsion Laboratory, Pasadena, Calif.

Arizona State University, Tempe, Ariz.
NASA Marshall Space Flight Center, Huntsville, Ala.
US Naval Research Laboratory, Washington
SRS Technologies, Huntsville, Ala.

5.6.2 Power/Energy Issues for Air

The current development of systems such as Global Hawk and UCAB, which ISR, SEAD and deep strike missions, have demonstrated that existing "off-the-shelf" propulsion systems are placed under such heavy demands that mission capability and operational utility can be severely limited. Future UAVs will address combat scenarios and are projected to require even greater demands for better fuel consumption, thrust, power extraction, cost and distortion tolerance. [43]

Two key metrics for propulsion are specific fuel consumption (SFC) for efficiency and mass specific power (MSP) for performance. *Figure 14: Specific Fuel Consumption Trends*[44] and *Figure 15: Mass Specific Power Trends*[45] indicate the anticipated improvements in performance over the next 23 years.

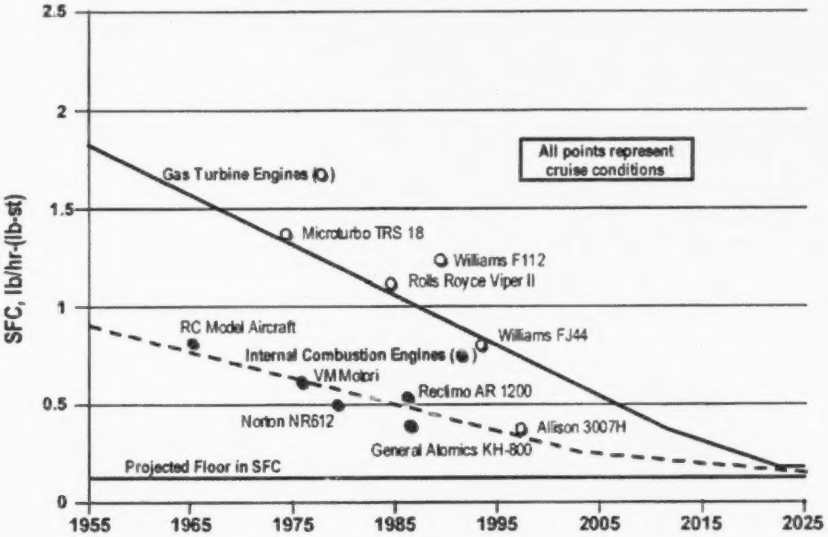

Figure 14: Specific Fuel Consumption Trends

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[43] Unmanned Aerial Vehicles Roadmap 2002-2007, Office of the Secretary of Defense, pg 74
[44] Unmanned Aerial Vehicles Roadmap 2002-2007, Office of the Secretary of Defense, pg 29
[45] Unmanned Aerial Vehicles Roadmap 2002-2007, Office of the Secretary of Defense, pg 30

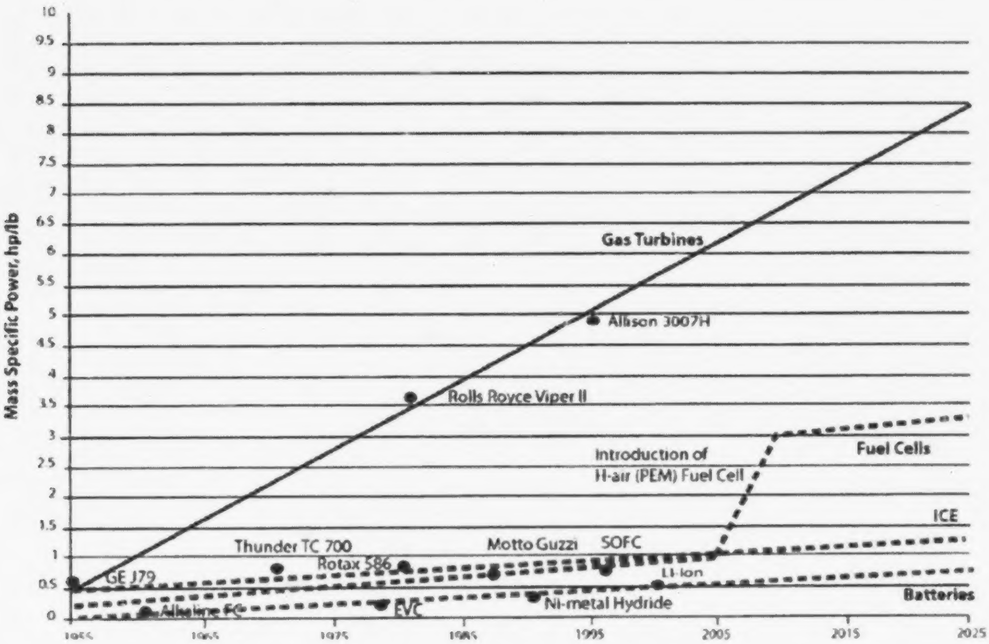

Figure 15: Mass Specific Power Trends

5.6.3 Power/Energy Issues for Ground

We were unable to identify unique power/energy issues during this study and recommend further efforts to evaluate this area.

5.6.4 Power/Energy Issues for Marine

We were unable to identify unique power/energy issues during this study and recommend further efforts to evaluate this area.

5.6.5 Power/Energy Issues for Underwater

We were unable to identify unique power/energy issues during this study and recommend further efforts to evaluate this area.

5.6.6 Power/Energy Issues for Cybots

We were unable to identify unique power/energy issues during this study and recommend further efforts to evaluate this area.

6 Vehicle Performance Optimization

This report has provided a high-level assessment of the capabilities and considerations required for autonomous unmanned vehicle operation in each of the defined battlespaces (when information was available given the time frame associated with assembling this report). It has delineated enabling technology streams and related them to technology integration and mission complexity. This section deals with vehicle performance optimization – an evolutionary path in any long-term vehicle design. Such optimization is, of course, mission-dependent.

6.1 Vehicle Scale

Vehicle Scale has significant implications for UXV Performance Optimization. It establishes the physical envelope for the vehicle. This in turn has significant effects on other performance factors. These include:

Payload – the smaller the vehicle, the smaller the payload;
Drag/Resistance – this is highly dependent on scale (e.g., low Reynolds numbers are associated with high drag; rolling resistance is high for small-ground vehicles);
Range – this is an optimization calculation between vehicle drag and fuel capacity which highly dependent on scale;
Detectability (signature) – other things being equal, the larger the vehicle, the easier it is to detect;
Cost – generally, the larger the vehicle, the higher the cost. Increasing cost makes it unlikely that the vehicle will be deemed expendable. This will affect the mission profile.

Ultimately, scale will be optimized for mission operational effectiveness and cost.

6.2 Range and Endurance

In general, range and endurance tend to be functions of the vehicle's power usage, weight and payload. Performance improvements for range and endurance can, therefore, be achieved by a measurable improvement in any or all of these three attributes of the vehicle. Existing efforts (see the section on Power/Energy) to improve the power per volume or weight of fuel will increase range as will efforts to use lighter composite material. As sensor suites become integrated with miniaturization, further improvement will be achieved. Current goals for some orbital or high altitude vehicles are six months' operation before returning to based for maintenance.

6.3 Maintainability

Maintainability refers to the level of effort, complexity or frequency of the maintenance of the UXVs. Currently, UAVs have a low reliability requiring frequent maintenance (according to Dyke Weatherington, of the US Office of the Secretary of Defense). As well, the expertise level necessary to maintain and operate these vehicles is not consistent with the experience and capability of the personnel ideally suited to use these devices. This complexity and frequency of maintenance has been rapidly improving over the last ten years as capability of the UXVs has increased, and experience in the field using and maintaining these devices has provided feedback into the development community and improved designs. Fully autonomous vehicles will require very high reliability achieved with a minimum of maintenance, or they could employ self-healing technology such as that employed by NASA. The complexity of the maintenance will need to be reduced with self-diagnostics and modular replacement with a minimal tools set. A commonality of modules and tools should be encouraged to reduce the logistics of in-the-field maintenance.

6.3.1 Maintainability Issues for Space

Outer space adds another twist to the maintenance activity. Access to the vehicle is achieved in one of two methods, either the vehicle re-enters the earth's atmosphere and returns to earth for maintenance or the vehicle is met in orbit by a re-enterable vehicle, such as the space shuttle, and maintenance is performed in orbit. This second approach is an extremely expensive approach to maintenance. This suggests the requirement for fault-tolerant design and re-mapable circuits to enable maintenance to be performed via ground instructions or actions taken by the vehicle. Another alternative will be space-based maintenance vehicles that autonomously travel from satellite to satellite performing repairs and parts replacement.

6.3.2 Maintainability Issues for Air

We were unable to identify unique maintainability issues during this study and recommend further efforts to evaluate this area.

6.3.3 Maintainability Issues for Ground

We were unable to identify unique maintainability issues during this study and recommend further efforts to evaluate this area.

6.3.4 Maintainability Issues for Marine

We were unable to identify unique maintainability issues during this study and recommend further efforts to evaluate this area.

6.3.5 Maintainability Issues for Underwater

We were unable to identify unique maintainability issues during this study and recommend further efforts to evaluate this area.

6.3.6 Maintainability Issues for Cyberbots

We were unable to identify unique maintainability issues during this study and recommend further efforts to evaluate this area.

6.4 Availability

Unmanned vehicles have the advantage of being able to remove many of the redundancies built into manned systems in an effort to reduce cost and complexity of the systems. The removal of systems tends to reduce maintenance and logistics costs as well. The negative impact of removing the redundant systems is the corresponding reduction in the survivability of the UXV.

6.5 Reliability

The issues surrounding reliability are orthogonal to availability and cost. A tradeoff is required when considering whether a system will have a low cost and high availability or high availability and high reliability. Some of the issues that need to be addressed to achieve high reliability are[46]:

- Subsystem failure detection and isolation
- Similar and dissimilar redundant sensor data processing and sensor fusion
- Self-awareness sensors and processing
- Fault decision-making and system reconfiguration

6.5.1 Reliability Issues for Space

We were unable to identify unique reliability issues during this study and recommend further efforts to evaluate this area.

6.5.2 Reliability Issues for Air

Reliable airborne vehicles must deal with the following conditions:[47]

- Runway incursions
- Near misses
- Flight plan deviations
- ATC / Pilot interactions
- Single failure points
- Cascading events
- Combinational events and operations conditions
- Reliability issues for ground
- Civilian road issues

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[46] Applications, Concepts and Technologies for Future Tactical UAVs pg 6-11

[47] Applications, Concepts and Technologies for Future Tactical UAVS, pg 9-15

6.5.3 Reliability Issues for Ground

We were unable to identify unique reliability issues during this study and recommend further efforts to evaluate this area.

6.5.4 Reliability Issues for Marine

The following issues will need to be addressed before the autonomous vehicles will earn the trust of the user and be considered reliable:

- Avoiding civilian surface traffic, and
- Sea-keeping (the ability to compensate for drift due to waves and current and maintain position at a fixed geographic position) in extreme weather.

6.5.5 Reliability Issues for Underwater

We were unable to identify unique reliability issues during this study and recommend further efforts to evaluate this area.

6.5.6 Reliability Issues for Cyberbots

We were unable to identify unique reliability issues during this study and recommend further efforts to evaluate this area.

6.6 Survivability

UXVs can be designed without the need for windows and fewer and smaller hatches allowing for lower or reduced observable attributes. This reduction in windows and hatches will allow for fewer seams and fewer possible failure points on the vehicle's surface. Being able to reduce the requirement for hatches will also enhance the ability to design the service for reductions in signature for radar, infrared, etc. Designing for survivability needs to be viewed from a mission perspective. If the UXV is ultimately a dispensable asset, then increasing the cost of the UXV to increase the survivability may not make sense. However, if mission requirements include the ability to reach a target while surviving a significant punishment, this would warrant the increase in cost.

Many of the aspects of survivability are tied to improvements in various systems to reduce: noise, heat signature, visibility, radar cross-section, etc. In addition, new and emerging technologies such as self-repairing structures and fault tolerant control systems could increase survivability without dramatic per unit cost increases. The self-repairing structures will be made out of composites, possible as a result of nanotechnology, that are capable of sealing small holes or gaps inflicted by small arms fire. Self-repairing or fault-tolerant control systems will be able to detect that the control systems currently in use are not performing correctly and could use other control structures to perform the same or sufficiently similar actions to allow the mission to continue after a failure. With technological advances in smart structures (structures that are able to reassemble themselves, expand and change size, redirect the forces acting on the structure thus changing the dynamics of the structure, etc.) the control systems could activate surrounding portions of the skin of the UXV to deform, or assume a control role.

6.7 Payload

Payload is fundamentally affected by the degree of autonomy that is built into the vehicle. For low levels of autonomy, surveillance/sensing equipment are deemed as payload – and perhaps the only payload. For high levels of autonomy, such equipment is inherent in the vehicle design. It becomes part of the vehicle rather than part of the payload.

Regardless of the nature of the payload, increases thereof dramatically affect vehicle size, power requirements, range, deployment, stealth, etc. Optimization of this problem is not new and will be mission-dependent.

6.8 Detectability (Stealth)

Much of the existing effort to provide stealth for manned vehicles will be directly transferable to unmanned vehicles. Such vehicles could have the added advantage of a reduction in the number of hatches, windows, etc. which will result in fewer joints, fewer material changes in the exterior and potentially better noise/visibility reduction with the same technology used for manned vehicles.

6.9 Cost

It is expected that unmanned vehicles should be inherently cheaper than equivalent manned systems. This belief stems from the idea that the vehicle can be smaller and can have human-centric systems removed, as they are not required. The US OSD estimate this savings as $1500 per pound and estimate that removing the pilot and air crew in UAVs will result in up to 5000 pounds[48] in cockpit weight being removed from the overall weight. The reduction in weight also reduces the requirements for a propulsion system, further reducing purchase cost as well as operational costs.

One of the prime drivers for the development of UXVs by the military has been the potential for a significant reduction of costs.[49] This cost reduction will result from the use of advanced composite manufacturing processes and a reduction in the cost of sensors. The cost of the ground support for existing UXVs is a significant portion of the operational cost of these systems, and increases in the affordability will result from reducing this portion of the operational costs. This reduction will initially occur with better man/machine interfaces, but ultimately it comes with the automation of more and more of the mission process (such as mission planning, interactions with ATC, get into position and then report back for instructions) relieving the human operator and eventually removing the operator altogether. The use of synthetic environments for training operators and warfighters to incorporate these systems into their tactical and strategic process will further reduce the overall operational cost.[50]

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[48] Unmanned Aerial Vehicles Roadmap 2002-2007, Office of the Secretary of Defense, pg 48, December 2002

[49] Applications, Concepts and Technologies for Future Tactical UAVs pg 2-16

A potential for reduced acquisition, operations and support costs may result from the following attributes[51]:

- Additional degree of design freedom unconstrained by on-board human operator considerations/limitations
- Reduced peace-time training and support infrastructure
- Increased stand-off precision engagement capability
- Missionized platform modularity and long-term storage potential
- Long endurance/high tempo operations
- Reduced human risk and political sensitivity to combat losses
- Automated mission functions for rapid reaction

These are, in general, applicable to all UXVs.

6.10 Autonomy

Autonomy has been defined[52] as the ability to function as an independent unit or element over an extended period of time, performing a variety of actions necessary to achieve pre-designated objectives while responding to stimuli produced by integrally contained sensors. This implies that the systems must have a situational awareness that enables the detection of threats, terrain understanding, detection of collision situations and targets of opportunity. The system must have multi-system communications networking, primarily focusing on communications, data/info relay and networking for multi-UXV or mixed manned/unmanned operations, as well as providing command and control information feedback. The motion capabilities need to be coupled with on-route route re-planning, reaction to identified threats and targets.[53]

Figure 16: Autonomous Control Level Trends shows an evolution of autonomous vehicles similar to the concept in Section A Road Map to Fully Autonomous Cooperative UXVs. The same concept applies for each of the battlespaces. The two axis of the graph remain the same, however, the curve shifts left or right slightly depending on the battlespace.

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[50] Applications, Concepts and Technologies for Future Tactical UAVs pg 2-16
[51] Applications, Concepts and Technologies for Future Tactical UAVs pg 3-3
[52] Applications, Concepts and Technologies for Future Tactical UAVs pg 5-1
[53] Applications, Concepts and Technologies for Future Tactical UAVs pg 6-9

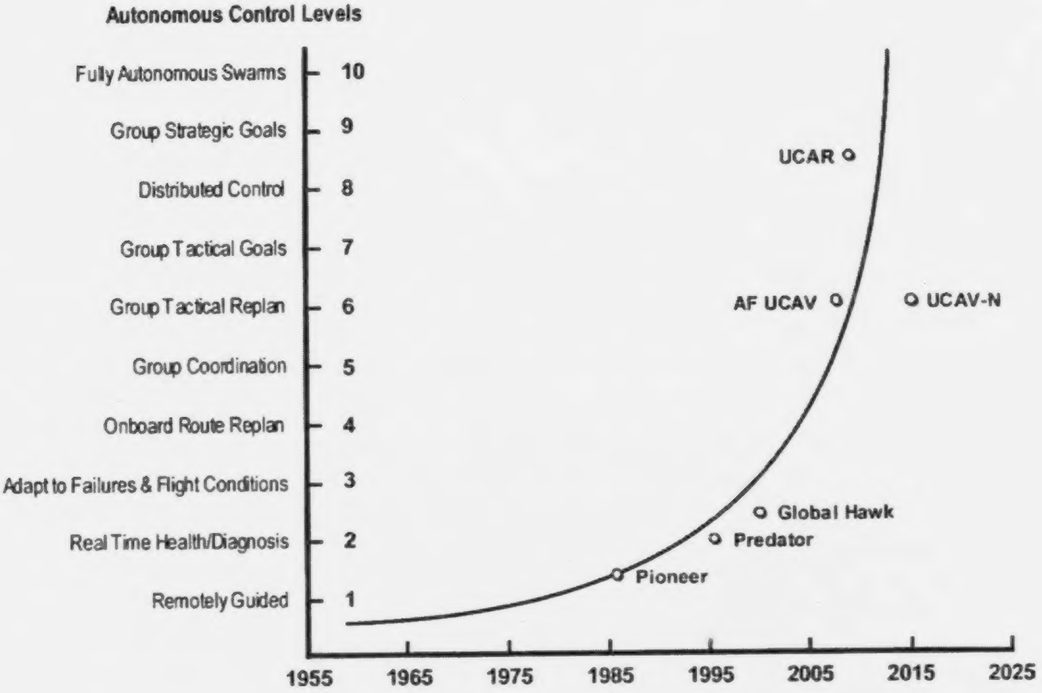

Figure 16: Autonomous Control Level Trends[54]

6.10.1 Autonomy Issues for Space

When considering the issue of an autonomous space vehicle, there are several activities currently performed by ground controllers that would need to be assumed by the autonomous system. These tasks include:
Adjusting for satellites' drift in orbit, which includes dealing with the following factors:

- Station keeping (remaining in its assigned position)
- Ability to know their location (required for station keeping)
- Ability to move to a specified new location (required for station keeping)

In addition, the autonomous system would need to perform:

- Heath monitoring
- Power shedding
- Realignment for solar storms to present a minimal configuration to the path of the solar dust in order to minimize potential for damage
- Realign receiving and transmitting antennas for optimal use by the ground stations as the vehicle moves
- Detect other vehicles and track where they are

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[54] Unmanned Aerial Vehicles Roadmap 2002-2007, Office of the Secretary of Defense, pg 41

- Detect small space debris and avoid during movement

6.10.2 Autonomy Issues for Air

The primary high-risk areas for which technological advances are required to enable autonomous operation of UAVs have been categorized[55] as:

- Real Time large scale optimization
- Autonomous Flight Management
- Integration
- Mission specific planning and behaviour

6.10.2.1 See but Don't be Seen by Civilian Systems

In order to eventually receive certification for operation in civilian air space, UAVs will need to be developed such that the burden of avoiding a mid-air conflict is assumed by the UAV's autonomous control. The manual of operations for both radar-controlled and non-radar-controlled airspace with both visual and instrument flight rules will need to be understood by the UAV along with the process of acknowledging and implementing the control instructions of the Air Traffic Controller. The different rules for the different mission areas will need to be known; for example, flight levels for specific direction of flight can change from country to country. NOTAMS (notice to Airman) information regarding restricted air space changes, new rules, etc. will continually need to be incorporated into the system. The goal is to make the UAV appear to Air Traffic Control (ATC) as just another piloted vehicle and to avoid civilian traffic such that a violation of separation rules never occurs.

6.10.3 Autonomy Issues for Ground

The major problems confronting the evolution of the autonomous ground vehicle include developing better or new capabilities to perform the following tasks:

- Road following
- Intersection detection
- Traffic avoidance
- Signal understanding (signs, lights, etc.)
- Terrain understanding/characterization
- Warfighter behaviour (tactical behaviour) adaptation for missions

The first five items on this list deal with situational awareness and the incorporation of this information into the path planning and collision avoidance systems. The solution to these problems includes new and improved sensors combined with intelligent processing of the sensed data to provide the necessary inputs to the path planning and collision avoidance systems.

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[55] Integrated Mission System Concepts and Technologies for Future Unmanned Combat Applications pg.79

6.10.4 Target Identification

Whether to increase survivability, perform a mission or support autonomy, UXVs will need to identify targets from within the world they operate. These targets could be mechanical or human. The target could be friendly, combatant or non-combatant and the system will need to be able to differentiate between all three with limited and obscured sensor returns from the object in question. "Today's technological capabilities for extracting information from vision systems enable robotic systems to be built that are good at the following tasks:

- Determining human faces in a scene
- Recognizing human faces from a relatively small library of faces as long as there is a full frontal view
- Finding eyes on faces
- Tracking moving objects from a stationary camera
- Determining the rough three-dimensional structure of a scene over distances of two or three meters
- Creating a detailed geometric model of objects
- Identifying saturated colors and skin-like colors.

These vision systems are not good for developing robotic systems that are good for the following tasks:

- Compensating for camera motion in tracking objects
- Recognizing whether a face is male or female, old or young
- Determining with accuracy where a face is looking
- Recognizing a face as it changes with time
- Differentiate the clothing from the body
- Identify the characteristics of material
- Recognizing general objects
- Recognizing partially obscured objects
- Identifying people when no skin is detected."[56]

The capabilities that the current vision systems do not have are all ones that will be required for target and threat identification to succeed. These include[57]

- The effect of pixel size on accuracy
- Knowledge of the vehicle's velocity vector must be in the order of cm/s to enable high-precision targeting
- Terrain model at target position with high-precision altitude information
- Integration of multiple images of the target area
- Coherent detection of changes in the image of the target with time
- Recognition through clutter, weather and changes in target attitude and appearance (i.e., extra equipment on-board a tank).

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[56] Flesh and Machines: How Robots will change us, Rodney A. Brooks, 2002, pg 90

[57] Integrated Mission System Concepts and Technologies for Future Unmanned Combat Applications pg.88

6.10.5 Interacting with Military Vehicles and Personnel

With the evolution of and eventual incorporation of micro UXVs into operational missions, command and control must be focussed to enable "non-specialist" operators to effectively use these tools. This will require a highly simple and intuitive control system which will allow one operator to control many such systems simultaneously. Integration of fully autonomous systems in a battlespace with friendly human forces will also involve significant controls on the overall systems functions to ensure that friendly fire events do not occur.

Small UXVs will likely be working in close proximity to manned and other unmanned systems. Although these systems will be small, they will contain enough mass, fuel and moving parts to seriously injure a human or decommission another unmanned system. Collision avoidance algorithms will be required to prevent such actions.

6.10.6 Autonomy Issues for Marine

We were unable to identify unique autonomy issues during this study and recommend further efforts to evaluate this area.

6.10.7 Autonomy Issues for Underwater

We were unable to identify unique autonomy issues during this study and recommend further efforts to evaluate this area.

6.10.8 Autonomy Issues for Cyberbots

We were unable to identify unique autonomy issues during this study and recommend further efforts to evaluate this area.

7 Symmetric and Asymmetric Threats

7.1 Disruptive Technologies, Asymmetric and Symmetric Warfare

Disruptive technologies are new or existing devices used in an innovative fashion that significantly alter established practices. Within a military context, disruptive technologies:

- Change the "business model" of the military or part thereof;
- Are evaluated on a different performance metric(s); and
- Can incubate in fringe commercial markets that are relevant to the military – or in fringe markets within the military itself.

In contrast, *sustaining technologies* foster improved product performance along an established trajectory. They also maintain an organization's business model. However, sustaining technologies often provide more features than customers need or want.[58] Regardless, the majority of the income derived from technological development is based on sustaining technologies.

The potential for UXVs to become disruptive in nature is very high. Clearly, these technologies could significantly alter the military business model. Performance metrics may be different or the UXV may be substantially improved for a given metric (e.g., endurance). If a UXV is deemed expendable, the risk calculation associated with the mission will change. If human operators are not on-board the vehicle, size constraints and mission constraints are altered.

Accordingly, UXVs will likely have a truly disruptive effect on the military and the incumbent players within the industrial complex which supports it. This has national and international economic implications.

The disruptive nature of UXVs (or any other technology or technology convergence) has the potential to be used in an asymmetric sense. Asymmetric warfare has all the hallmarks of a disruptive technology. Asymmetric warfare:

- Establishes a new business, or operational, model. It does not follow normal military structure or process;
- Competes on different performance metrics. The focus is on civilian targets and the generation of fear using limited equipment and resources;
- Is ultimately a fringe military activity; nation states are not necessarily directly involved.

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[58] Christensen, Clayton, *The Innovator's Dilemma*, HBS Press, 1997.

The low-cost UXV is a possible fit for an asymmetric warfare model. The implications of this are very significant. Numerous external or internal groups could potentially turn virtually any low-cost weapon against the society that created it. It is necessary to consider countermeasures to such weapons in the early stages of the development cycle.

Symmetric warfare is another consideration. Generally (though not universally), high-cost, complex weapon systems are designed to counter symmetric threats (other high-cost, complex weapons systems). Consideration of UXV autonomy, in a symmetrical context, adds additional demands on the development of enabling technologies. The implications of a symmetric war based on UXVs have yet to be thoroughly explored.

As outlined earlier in this document, policy implications are beyond the scope of this report. It is sufficient to state here that technological disruption, asymmetric and symmetric UXV warfare need to be given careful thought. Furthermore, such considerations will have a direct impact on UXV development from a technological perspective.

8 Canadian Capabilities in Robotics

The Canadian capabilities to develop and research the enabling technologies for robotics have largely been focussed for the last ten years around the Canadian Space Agency (CSA) Mobile Servicing System. The dual Arm system was selected for various reasons such as the extension of the successful Canadarm used on the Space Shuttle and the view that industrial robots would provide a significant boost to Canadian manufacturing capabilities. As a result, Canada has significant expertise in various areas of enabling technologies while very little in areas that will be required for autonomous cooperative vehicles. There are 169 university and college-level educational institutions in Canada. Of these institutions, the following 28 have the academic staff and research facilities to pursue research on the enabling technologies that underlie the Autonomous Cooperative UXV. *Table 14: Research Universities and Enabling Technology Areas* presents the areas in which each of the organizations has developed a capability to perform research.

The detailed assessment of Canadian capabilities as viewed by NSERC has been summarized in Appendix B. A short summary of the issues as seen by PRECARN/IRIS researchers for the path forward in autonomous robotics is presented in Appendix C.

In *Table 14: Research Universities and Enabling Technology Areas,* the areas of expertise for each of the major universities in Canada has been identified which relate to technologies of interest to an Autonomous Vehicles program. This data is an amalgamation of NSERC-funded grants and scholarships with published information on each university Web site. Furthermore, In Table 17: Number of Universities Receiving NSERC Funding per Research Area, Table 18: Universities/organizations NSERC Grants by Technology Area, and Table 19: Technology Area supported by NSERC with Funding, an analysis of the research grants and scholarships issued by the NSERC for the year 2002 have been presented. These grants are used by professors to fund masters and PhD students and is a good indicator of the professors' interests. One important note looking at this data is the low number of grants for research into communications. It is suggested that at the time the grant requests were prepared, early 2001, there was significant private sector funding for communications research and the professors did not need to rely on NSERC for this type of funding.

In Table 20: Summary of Enabling Technology and Research Efforts the data presented in the earlier tables have been summarized to provide a view of the level of effort and capability of Canadian university researchers to support work in the enabling technologies.

Table 21: Researches Active in Multi Robot Systems is a list of researchers identified as leaders/active in multi-robotic systems (Swarms).

Table 17: Number of Universities Receiving NSERC Funding per Research Area shows the number of grants and scholarships awarded by NSERC to the various universities in Canada.

Table 14: Research Universities and Enabling Technology Areas indicates that intelligent software and sensing research is well-represented at Canadian universities. However, the Defence community will need to oversee a portion of this research so that it meets their needs.

The data in Table 14: Research Universities and Enabling Technology Areas also indicates the gaps in Canadian university research and development for the UXV enabling technology streams. These are:

- Robotics
- Mobility
- Navigation

Additional areas, which are somewhat lean, are:

- Communications
- Power

If UXVs are going to become part of the Canadian industrial landscape, these gaps will need to be addressed – through direct efforts, national or international partnering. Such partnering may occur through the Canadian Space Agency (CSA), NSERC, PRECARN and/or IRIS. The CSA has demonstrated that a focussed effort on a particular mission can galvanize university research efforts. Their approach to basic technology research is as follows.

CSA conducted research in basic technology for the Canadarm and the Mobile Servicing Station (MSS). To achieve the desired outcomes, they:

- Identified core technology areas where the expertise in Canada was lacking, in order to develop the systems; and

- Invited university-industry teams to prepare proposals for research projects in the identified technology areas.

The research projects had three phases of funding. At the conclusion of each phase, the university-industry teams that had won the earlier phase competed with each other for funding in the next phase. The phases were structured as follows:

- The first phase had a maximum value of $100,000. Typically, this phase involved a technology investigation, possibly some prototyping, and the development of a phase 2 project plan.

- The second phase was funded to a maximum of $1,000,000 (typically one in three first-phase teams were awarded phase 2 projects). Phase 2 was a technology demonstration project and required the team to provide some level of matching funds and to show a commercialization path for the effort. As part of the evaluation, the potential that the results of the effort would lead to a commercial product for one or more members of the team was assessed; the commitment by the team to commercialize the effort was also considered.

- The third phase was only funded if the technology was to be incorporated into the Canadarm or the MSS.

This type of research mechanism may offer attractive benefits to DND and provide a strong research pipeline for autonomous UXV deployment by 2025. In addition, utilization of the existing agreements between DND and NSERC, PRECARN/IRIS, NRC, etc. to partially fund their programs would ensure research efforts are funded by these groups that will support DND's goals.

Table 14: Research Universities and Enabling Technology Areas

University	Robotics	Dynamics	Mobility	Navigation	Intelligent Software	Sensing	Communications	Control Systems	Power	Materials
University of Alberta*					X	X	X	X		X
University of Calgary*		X			X	X		X		
Simon Fraser University*		X			X	X	X	X		
University of Victoria*					X					
University of Manitoba*		X			X	X		X		X
Memorial University of Newfoundland*	X		X		X					
Dalhousie University*			X		X	X			X	
Brock University*					X					
Carleton University*		X			X		X	X		
McMaster University*		X			X	X				
Queen's University*		X		X	X	X		X		X
Royal Military College of Canada*	X				X					X
Ryerson University*					X	X		X		
University of Guelph*		X			X	X				X
University of Ottawa*		X			X	X				X
University of Toronto*					X	X		X	X	
University of Waterloo*		X			X	X		X		X
University of Western Ontario*		X			X	X		X		
University of Windsor*					X	X				
Bishop's University*										
Concordia University*										
McGill University*		X			X	X		X	X	X
Université de Montréal*		X			X	X				
Université du Québec*, central		X			X	X		X		X
Université de Sherbrooke*										
University of Regina*										
University of Saskatchewan*										

University	**Robotics**	**Dynamics**	**Mobility**	**Navigation**	**Intelligent Software**	**Sensing**	**Communications**	**Control Systems**	**Power**	**Materials**
University of British Columbia		X			X	X		X		X
University of New Brunswick					X			X		
University of Regina					X					
University of Saskatchewan					X	X		X		
York University		X			X	X				

In addition, a number of organizations provide centres of excellence in specific areas. These centres can be located at a specific university or can be an amalgamation of several universities across Canada. These groups have been listed with the research focus in Table 16: Centres of Excellence in Canada.

The Governmental Organizations and Non-Governmental Organizations that are facilitating or performing research in enabling technologies are listed in Table 15: Governmental Organizations Facilitating Enabling Technologies.

Table 15: Governmental Organizations Facilitating Enabling Technologies

Organization	Research/enabling
Canadian Space Agency	Research/enabling
Defence Research and Development Canada	Research/enabling
National Research Council of Canada	Research/enabling
PRECARN/IRIS	Enabling
NSERC	Enabling
Fisheries and Oceans	Enabling
Atomic Energy of Canada Ltd.	Enabling
Environment Canada	Enabling
Alberta Research Council	Enabling
Ontario Research Foundation	Enabling
Other Provincial Research Councils	Enabling

Canadian Companies

According to PRECARN, the Canadian companies actively involved in research supporting autonomous unmanned vehicles include:

1. MD Robotics, Toronto, Ontario
2. Inuktun, Nanaimo, BC
3. Interational Submarine Enterprise (ISE), Port Coquitlam, BC
4. Intrignia, St. John's, Newfoundland

Table 16: Centres of Excellence in Canada

Centre of Excellence	Robotics	Dynamics	Mobility	Navigation	Intelligent Software	Sensing	Communications	Control Systems	Power	Materials
National Institute for Nanotechnology National Research Council Canada and University of Alberta						X				X
Canadian Institute for Telecommunications Research (CITR)							X			
Microelectronics Research Network (MICRONET)										
Institute for Robotics and Intelligent Systems (IRIS)	X				X					
Intelligent Sensing for Innovative Structures (ISIS)						X				
Canadian Institute for Photonics Innovations (CIPI)										
Mathematics of Information Technology and Complex Systems (MITACS)		X			X			X		
TeleLearning Network of Centres of Excellence (TeleLearning-NCE)										
Communications and Information Technology Ontario (CITO)							X			
Centre for Research in Earth and Space Technology (CRESTech)	X	X			X	X				
Materials and Manufacturing										X

Centre of Excellence	**Robotics**	**Dynamics**	**Mobility**	**Navigation**	**Intelligent Software**	**Sensing**	**Communications**	**Control Systems**	**Power**	**Materials**
Ontario (MMO)										
Photonics Research Ontario (PRO)							X			
Telecommunications Research Laboratories – TRLabs (Alberta)							X			
Advanced Systems Institute (BC)					X					
The Canada Foundation for Innovation (CFI)										

In Table 17: Number of Universities Receiving NSERC Funding per Research Area, Table 18: Universities/organizations NSERC Grants by Technology Area, and Table 19: Technology Area supported by NSERC with Funding, an analysis of the research grants and scholarships issued by the NSERC for the year 2002 have been presented. These grants are used by professors to fund masters and PhD students and is a good indicator of the professors' interests. One important note looking at this data is the low number of grants for research into communications. It is suggested that at the time the grant requests were prepared, early 2001, there was significant private sector funding for communications research and the professors did not need to rely on NSERC for this type of funding.

In Table 20: Summary of Enabling Technology and Research Efforts the data presented in the earlier tables have been summarized to provide a view of the level of effort and capability of Canadian university researchers to support work in the enabling technologies.

Table 21: Researches Active in Multi Robot Systems is a list of researchers identified as leaders/active in multi-robotic systems (Swarms).

Table 17: Number of Universities Receiving NSERC Funding per Research Area

Area of Study	Sub Area of Study	Total
Artificial Intelligences	Control Systems	4
	Learning and Adaptation	12
	Multi Agent Planning	7
	Perception	5
	Planning	10
Artificial Intelligences Total		38
Electrical Engineering	Control Systems	4
	Dynamics	1
	Health Maintenance	1
	Materials	4
	Perception	6
	Planning	1
Electrical Engineering Total		17
Mesoscopic physics	Materials	8
Mesoscopic physics Total		8
Other sources of energy (solar, wind, etc.)	Power	6
Other sources of energy (solar, wind, etc.) Total		6
Robotics	Communications	2
	Control Systems	24
	Dynamics	26
	Health Maintenance	3
	Human Machine Interfacing	1
	Learning and Adaptation	7
	Mobility	1
	Mobility/Cyberbots	1

Area of Study	Sub Area of Study	Total
	Multi Agent Planning	2
	Navigation	2
	Perception	43
	Planning	8
	(blank)	54
Robotics Total		174
(blank)	(blank)	1
(blank) Total		1
Grand Total		244

Table 18: Universities/organizations NSERC Grants by Technology Area

University	Sub Area	Data	Total
Brock University	Learning and Adaptation	Count of Title	1
		Sum of Amount	8156
Carleton University	Control Systems	Count of Title	2
		Sum of Amount	41000
	Dynamics	Count of Title	2
		Sum of Amount	43296
	Learning and Adaptation	Count of Title	2
		Sum of Amount	57600
	Multi Agent Planning	Count of Title	1
		Sum of Amount	10000
	(blank)	Count of Title	1
		Sum of Amount	17300
Concordia University	Control Systems	Count of Title	1
		Sum of Amount	19560
	Dynamics	Count of Title	1
		Sum of Amount	19950
	Perception	Count of Title	1
		Sum of Amount	45000
	Power	Count of Title	1
		Sum of Amount	24038
Dalhousie University	Mobility/Cyberbots	Count of Title	1
		Sum of Amount	32000
	Perception	Count of Title	1
		Sum of Amount	25620
	Power	Count of Title	1
		Sum of Amount	19459
École de technologie supérieure	Control Systems	Count of Title	1
		Sum of Amount	70080
	Dynamics	Count of Title	1
		Sum of Amount	22271
	Perception	Count of Title	2
		Sum of Amount	40790
	(blank)	Count of Title	1

University	Sub Area	Data	Total
		Sum of Amount	17300
École Polytechnique de Montréal	Dynamics	Count of Title	3
		Sum of Amount	152306
	Human Machine Interfacing	Count of Title	1
		Sum of Amount	44268
	Perception	Count of Title	2
		Sum of Amount	49950
	Planning	Count of Title	1
		Sum of Amount	21271
	(blank)	Count of Title	1
		Sum of Amount	4000
Institut national de la recherche scientifique	Power	Count of Title	2
		Sum of Amount	149662
McGill University	Control Systems	Count of Title	2
		Sum of Amount	78990
	Dynamics	Count of Title	1
		Sum of Amount	15450
	Learning and Adaptation	Count of Title	1
		Sum of Amount	39270
	Materials	Count of Title	3
		Sum of Amount	173220
	Perception	Count of Title	7
		Sum of Amount	229690
	Power	Count of Title	1
		Sum of Amount	22400
	(blank)	Count of Title	2
		Sum of Amount	21300
McMaster University	Dynamics	Count of Title	1
		Sum of Amount	21000
	Perception	Count of Title	2
		Sum of Amount	98200
	(blank)	Count of Title	2
		Sum of Amount	23100
Memorial University of Newfoundland	(blank)	Count of Title	2
		Sum of Amount	36400
Queen's University	Control Systems	Count of Title	1
		Sum of Amount	24000
	Dynamics	Count of Title	2
		Sum of Amount	54690
	Health Maintenance	Count of Title	1
		Sum of Amount	20600
	Materials	Count of Title	1
		Sum of Amount	32456
	Navigation	Count of Title	1
		Sum of Amount	17500
	Perception	Count of Title	1
		Sum of Amount	12930
Ryerson Polytechnic University	Control Systems	Count of Title	2

University	Sub Area	Data	Total
		Sum of Amount	36000
	Perception	Count of Title	2
		Sum of Amount	38698
Simon Fraser University	Communications	Count of Title	1
		Sum of Amount	34000
	Control Systems	Count of Title	2
		Sum of Amount	85050
	Dynamics	Count of Title	1
		Sum of Amount	31000
	Perception	Count of Title	2
		Sum of Amount	46305
	Planning	Count of Title	2
		Sum of Amount	56875
Trent University	(blank)	Count of Title	2
		Sum of Amount	23000
Université de Moncton	Dynamics	Count of Title	1
		Sum of Amount	18315
Université de Montréal	Dynamics	Count of Title	1
		Sum of Amount	30345
	Learning and Adaptation	Count of Title	2
		Sum of Amount	67000
	Perception	Count of Title	1
		Sum of Amount	24000
Université de Sherbrooke	Control Systems	Count of Title	1
		Sum of Amount	21945
	Materials	Count of Title	2
		Sum of Amount	61308
	Perception	Count of Title	1
		Sum of Amount	22050
	(blank)	Count of Title	2
		Sum of Amount	23100
Université du Québec à Hull	Control Systems	Count of Title	1
		Sum of Amount	36850
Université du Québec à Montréal	Perception	Count of Title	1
		Sum of Amount	17325
Université du Québec en Abitibi-Témiscamingue	(blank)	Count of Title	1
		Sum of Amount	4000
Université Laval	Dynamics	Count of Title	3
		Sum of Amount	181418
	Materials	Count of Title	1
		Sum of Amount	40000
	Perception	Count of Title	2
		Sum of Amount	55875
	Planning	Count of Title	1
		Sum of Amount	30850
	(blank)	Count of Title	4
		Sum of Amount	88487
University College of the Cariboo	Perception	Count of Title	1

University	Sub Area	Data	Total
		Sum of Amount	8333
University of Alberta	Multi Agent Planning	Count of Title	1
		Sum of Amount	37980
	Communications	Count of Title	1
		Sum of Amount	24000
	Control Systems	Count of Title	2
		Sum of Amount	144377
	Learning and Adaptation	Count of Title	1
		Sum of Amount	145000
	Materials	Count of Title	1
		Sum of Amount	9240
	Perception	Count of Title	2
		Sum of Amount	46900
	Planning	Count of Title	3
		Sum of Amount	63954
	(blank)	Count of Title	2
		Sum of Amount	31100
University of British Columbia	Control Systems	Count of Title	4
		Sum of Amount	158529
	Dynamics	Count of Title	1
		Sum of Amount	17510
	Learning and Adaptation	Count of Title	1
		Sum of Amount	18000
	Materials	Count of Title	1
		Sum of Amount	14000
	Multi Agent Planning	Count of Title	1
		Sum of Amount	35000
	Perception	Count of Title	3
		Sum of Amount	122805
	(blank)	Count of Title	6
		Sum of Amount	64447
University of Calgary	Control Systems	Count of Title	1
		Sum of Amount	18315
	Dynamics	Count of Title	1
		Sum of Amount	25000
	Perception	Count of Title	2
		Sum of Amount	34000
	(blank)	Count of Title	1
		Sum of Amount	4000
University of Guelph	Dynamics	Count of Title	1
		Sum of Amount	21771
	Learning and Adaptation	Count of Title	1
		Sum of Amount	19000
	Mobility	Count of Title	1
		Sum of Amount	15000
	Multi Agent Planning	Count of Title	1
		Sum of Amount	31000
	Navigation	Count of Title	1

University	Sub Area	Data	Total
		Sum of Amount	20790
	Perception	Count of Title	1
		Sum of Amount	19950
	(blank)	Count of Title	3
		Sum of Amount	40400
University of Lethbridge	Planning	Count of Title	1
		Sum of Amount	10000
University of Manitoba	Control Systems	Count of Title	2
		Sum of Amount	68550
	Materials	Count of Title	1
		Sum of Amount	49220
	Multi Agent Planning	Count of Title	1
		Sum of Amount	17000
	Perception	Count of Title	1
		Sum of Amount	39270
	(blank)	Count of Title	2
		Sum of Amount	21300
University of New Brunswick	Control Systems	Count of Title	1
		Sum of Amount	34650
	Learning and Adaptation	Count of Title	1
		Sum of Amount	15015
	Multi Agent Planning	Count of Title	1
		Sum of Amount	10000
University of Ottawa	Dynamics	Count of Title	2
		Sum of Amount	63730
	Health Maintenance	Count of Title	1
		Sum of Amount	17000
	Learning and Adaptation	Count of Title	2
		Sum of Amount	61989
	Materials	Count of Title	1
		Sum of Amount	13000
	Perception	Count of Title	3
		Sum of Amount	51500
	Planning	Count of Title	1
		Sum of Amount	23472
University of Regina	Multi Agent Planning	Count of Title	1
		Sum of Amount	25000
University of Saskatchewan	Control Systems	Count of Title	2
		Sum of Amount	56650
	Multi Agent Planning	Count of Title	1
		Sum of Amount	17000
	Perception	Count of Title	1
		Sum of Amount	49938
University of Toronto	Control Systems	Count of Title	2
		Sum of Amount	154000
	Health Maintenance	Count of Title	1
		Sum of Amount	19000
	Learning and Adaptation	Count of Title	3

University	Sub Area	Data	Total
		Sum of Amount	144060
	Perception	Count of Title	4
		Sum of Amount	127000
	Planning	Count of Title	4
		Sum of Amount	203140
	Power	Count of Title	1
		Sum of Amount	38000
	(blank)	Count of Title	3
		Sum of Amount	27100
University of Victoria	Health Maintenance	Count of Title	1
		Sum of Amount	32000
	Learning and Adaptation	Count of Title	1
		Sum of Amount	23188
	(blank)	Count of Title	2
		Sum of Amount	36400
University of Waterloo	Control Systems	Count of Title	2
		Sum of Amount	60890
	Dynamics	Count of Title	2
		Sum of Amount	62000
	Learning and Adaptation	Count of Title	1
		Sum of Amount	21000
	Materials	Count of Title	1
		Sum of Amount	23000
	Perception	Count of Title	2
		Sum of Amount	39480
	Planning	Count of Title	1
		Sum of Amount	22893
	(blank)	Count of Title	7
		Sum of Amount	78950
University of Western Ontario	Learning and Adaptation	Count of Title	1
		Sum of Amount	23100
	Control Systems	Count of Title	3
		Sum of Amount	210603
	Dynamics	Count of Title	1
		Sum of Amount	20000
	Multi Agent Planning	Count of Title	1
		Sum of Amount	24727
	Perception	Count of Title	2
		Sum of Amount	44869
	(blank)	Count of Title	1
		Sum of Amount	4000
University of Windsor	Perception	Count of Title	2
		Sum of Amount	77500
	Planning	Count of Title	4
		Sum of Amount	117420
	(blank)	Count of Title	1
		Sum of Amount	16000
University of Winnipeg	Dynamics	Count of Title	1

University	Sub Area	Data	Total
		Sum of Amount	17000
Wilfrid Laurier University	Perception	Count of Title	1
		Sum of Amount	14556
York University	Dynamics	Count of Title	1
		Sum of Amount	72000
	Perception	Count of Title	3
		Sum of Amount	73038
	Planning	Count of Title	1
		Sum of Amount	28000
	(blank)	Count of Title	1
		Sum of Amount	19100

Table 19: Technology Area supported by NSERC with Funding

Sub Area	Data	Total
Communications	Count of Title	2
	Sum of Amount	58000
Control Systems	Count of Title	32
	Sum of Amount	1320039
Dynamics	Count of Title	27
	Sum of Amount	889052
Health Maintenance	Count of Title	4
	Sum of Amount	88600
Human Machine Interfacing	Count of Title	1
	Sum of Amount	44268
Learning and Adaptation	Count of Title	19
	Sum of Amount	677378
Materials	Count of Title	12
	Sum of Amount	415444
Mobility	Count of Title	1
	Sum of Amount	15000
Mobility/Cyberbots	Count of Title	1
	Sum of Amount	32000
Multi Agent Planning	Count of Title	9
	Sum of Amount	207707
Navigation	Count of Title	2
	Sum of Amount	38290
Perception	Count of Title	54
	Sum of Amount	1473072
Planning	Count of Title	19
	Sum of Amount	577875
Power	Count of Title	7
	Sum of Amount	273559
(blank)	Count of Title	54
	Sum of Amount	674034

Table 20: Summary of Enabling Technology and Research Efforts

Enabling Technology	**Canadian Research Effort** ***# of Grants*** ***Ave. $/Grant***	**Highest Intensity of Effort (University Locations)**	**$ Currently being Expended**
Robotics, Dynamics and Mobility	29 $32k/grant	Laval, Ecole Poly, Carleton, Queen's, Guelph, Ottawa, Waterloo	$936k
Intelligent S/W, Sensing and Navigation	108 $29k/grant	Toronto, McGill, Alberta, Ottawa, Windsor, UBC	$3,107k
Control Systems	32 $41k/grant	UBC, Western	$1,320k
Materials	12 $35k/grant	McGill, Sherbrooke, Alberta, Laval, Queen's, UBC, Man., Ottawa, Waterloo	$415k
Communications (see note below)	2 $29k/grant	Simon Fraser, Alberta	$58k
Power/Energy Systems	7 $39k/grant	Concordia, Dalhousie, McGill, Toronto	$274k

Note: Communications funding was heavily influenced by private-sector activity.

People

Active researchers in the field of multi-robot systems are listed in Table 21: Researches Active in Multi Robot Systems.

Table 21: Researches Active in Multi Robot Systems

Country	Name	Research Facility
US	Ronald Arkin	Georgia Institute of Technology - Mobile Robot Laboratory
US	Tucker Balch	Georgia Institute of Technology - College of Computing
GE	Wolfram Burgard	Albert-Ludwigs-Universität Freiburg - Autonome Intelligente Systeme
CA	Gregory Dudek	McGill University - Center For Intelligent Machines
US	Kurt Konolige	Stanford University - Computer Science Department
US	Dieter Fox	University of Washington - Artificial Intelligence Research group
CA	C. Ronald Kube	University of Alberta - Collective Robotic Intelligence Project (CRIP)
US	Maja Mataric	University of Southern California - The Robotics Research Laboratory

CA	Evangelos E. Milios	York University - Vision, Graphics and Robotics Laboratory
US	Lynne Parker	Oak Ridge National Laboratory - Computational Intelligence Group
US	Alan Schultz	Navy Center for Applied Research in Artificial Intelligence
US	Sebastian Thrun	Carnegie Mellon University - Robotics Institute

The following is a list of Canadian professors (and their associated university) who represent Canadian leaders in the technology areas of Intelligent S/W, Sensing and Navigation along with their individual area of expertise.

Complexity Theory and Algorithms
1. Toronto: Stephen, Allan Borodin
2. Waterloo: Ian Munro (data structures), Prabhakar Ragde and Douglas Stinson
3. UBC: Nick Pippenger and Anne Condon
4. McGill: Luc Devroye

Computational Geometry
1. McGill: David Avis, Godfried Toussaint, Luc Devroye
2. UBC: David Kirkpatrick
3. Carleton: Frank Dehne and J¨org Sack, Prosenjit Bose

Logic and Computation
1. Toronto: Stephen Cook
2. McGill: Denis Thérien
3. Prakash Panangaden
4. Ottawa: Phil Scott
5. Toronto: Leonid Libkin
6. UWO: Helmut Jurgensen

Quantum Computing and Quantum Cryptography
1. Montreal: Gilles Brassard
2. McGill: Claude Crepeau
3. Waterloo: Michele Mosca
4. Calgary: John Watrous
5. UBC: Nick Pippenger

Artificial Intelligence
1. Toronto: Hector Levesque, Ray Reiter, Geoff Hinton, Mark Fox, John Mylopoulos, Craig Boutilier, Fahiem Bacchus, Graeme Hirst
2. UBC: Alan Mackworth, David Poole
3. Alberta: Jonathan Schaeffer
4. Waterloo: Nick Cercone

Computer Vision:
1. Toronto: Allan Jepson

2. York: John Tsotsos
3. UBC: David Lowe, Jim Little, Bob Woodham
4. McGill: Jim Clark
5. SFU: Brian Funt
6. Concordia Ching Suen, Adam Krzyzak
7. UWO: XiaolinWu
8. McMaster: Tom Luo
9. McGill: Luc Devroye, Godfried Toussaint

Glossary[59, 60, 61]

Agent: The programming concept of a software agent stems from the range of subjects of artificial intelligence, for which there has so far been no uniform definition. The term generally refers to an instance that tries to achieve, by means of autonomous action, internal and external objectives, set by the user. The main components of an agent are its knowledge base and its inference engine by means of which it can interpret information, draw conclusions and draw up plans for further actions. In addition, an agent is able to communicate with other agents and to interact with its environment via sensors or actors and effectors. Thus an agent is an intelligent automation component into which the different methods of computational intelligence such as fuzzy logic, neural networks, etc. can be integrated in an elegant manner.

Artificial Intelligence: The programming and ability of a robot to perform functions that are normally associated with human intelligence, such as reasoning, planning, problem solving, pattern, recognition, perception, cognition, understanding, learning, speech recognition and creative response.

Attributes: Describes features and properties.

Automation: The capability of a machine or its components to perform tasks previously done by humans. Usually accomplished by a subsystem of a larger system or process, performance of tasks can be cued by humans or a point in the process. Examples are an autoloader in an artillery system or machine welding of parts on an assembly line.

Autonomous: A mode of control of a UXV wherein the UXV is self-sufficient. The UXV is given its global mission by the human, has been programmed to learn from and responding to its environment, and operates without further human interventions.

Classes of UGVs: The Joint Robotics Program Office of the United States Department of Defense postulates several classes of UGVs, based upon weight:

- Micro: < 8 pounds
- Miniature: 8 – 30 pounds
- Small (light) 31- 400 pounds
- Small (medium) 401 – 2,500 pounds
- Small (heavy): 2,500 – 20,000 pounds
- Medium: 20,001 – 30,000 pounds
- Large: > 30,000 pounds

Computation for Sensors: Calculates observed entity attribute values generated by the grouping hypothesis.

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[59] Joint Robotics Program Master Plan FY 2002, OUSD (AT&L) S&ST/LAND Warfare, Washington DC, Section 8.2, pg 122 - 124. plus other definitions

[60] Applications, Concepts and Technologies for Future Tactical UAVs pg 5-18

[61] Applications, Concepts and Technologies for Future Tactical UAVs pg 6-4

Cooperative Algorithms: The ability of two or more UXVs to share data, coordinate their maneuver and perform tasks synergistically.

Data and Network Structures: State variables, attributes, entity frames, relationships, images, terrain, rules, equations and recipes.

Data Link: The means of connecting one part of the UXV system with another part of the system for the purposes of transmitting and receiving data. Examples of technologies used as UXV data links are radio frequency, fiber optics and laser.

Detection, Recognition, Classification: Determines the correlation or match between estimated attributes of entities observed in the real world and corresponding attributes of entity classes stored in the system's knowledge base.

Embodiment: An embodied creature or robot is one that has a physical body and experiences the world, at least in part, directly through the influence of the world on that body. A more specialized type of embodiment occurs when the full extent of the creature is contained within that body.

Entity, Event Frames: Representation of entities and events by frames that contain lists of state variables as well as attributes and relationships.

Expendable: A UXV that may be consumed in use and may be dropped from stock record accounts when it is issued or used.

Filtering/Recursive Estimation for Sensor Data: Computes best estimates (over space/time window) of entity attribute values based on correlation and differences between predicted and observed attribute values. Also statistical properties such as confidence/covariance in/of estimated values are computed.

Grouping: Integrates or organizes spatially and/or temporally contiguous sub-entities with similar attributes into entities.

Images: Contain information about position, orientation (aspect) of entities and objects in the world. Are also important for display of situations to humans.

Intelligent Mobility: Intelligent mobility, or the ability to move up and over obstacles, avoid obstacles in the vehicles path, and to move in novel ways using advanced locomotion and artificial intelligence is an inherent requirement in all future robotic systems and will support a range of evolving requirements.

JAUGS (Joint Architecture for Unmanned Ground Systems)[62] An upper-level design for interfaces within the domain of Unmanned Ground Vehicles. It is component-based, message-passing architecture that specifies data formats and methods of communications among computing nodes. It defines messages and component behaviours that are independent of technology, computer hardware and vehicle platforms and isolated from mission.

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[62] Joint Robotics Program Master Plan FY 2002, OUSD (AT&L) S&ST/LAND Warfare, Washington DC, Section 8.2, pg 122 - 124.

Knowledge: Data and info structure representing situational status, events and the dynamic world model.

Line-of-sight: (1) Visually, a condition that exists when there is no obstruction between the viewer and the object being viewed. (2) In radio frequency communications, a condition that exists when transmission and reception is not impeded by an intervening object, such as dense vegetation, terrain, man-made structures or the curvature of the earth, between the transmit and receive antennas.

Man-machine interface: The means by which the human operator interacts with the UXV system. It includes the software applications, graphics and hardware that allow the operator to effectively give instructions to or receive data from the UXV.

Manipulator: In robotics, a mechanism consisting of an arm and an end effector. It contains a series of segments, jointed or sliding relative to one another, for the purpose of modifying, grasping, emplacing and moving objects. A manipulator usually has several degrees of freedom.

Man portable: A UXV or components of a disassembled UXV, capable of being carried by one man over long distances without serious degradation of performance of his normal duties. The upper weight limit is 31 pounds per individual.

Man transportable: A UXV usually transported in another vehicle that has integrated provisions for periodic handling by one or more individuals for limited distances (100-500 meters). The upper weight limit is 65 pounds per individual.

Maps: Give a view of the terrain overlaid with labels, icons, text, etc. that provide necessary information for situational assessment.

Marsupial: A design concept for UXVs where a larger UXV carries one or more smaller UXVs either inside it or attached to it for later deployment.

Mission module: A self-contained assembly installed on a UXV that enables the unmanned platform to perform functions that have military value. It can be easily installed and replaced by another type of mission module.

Mission planning: The process in which a human operator devises tactical goals, a route (general or specific), and timing for one or more UXVs. Consideration includes terrain, weather and location of friendly forces, fire support and mission modules. The mission planning process may be accomplished on a computer or OCU for downloading to the UXV.

Mobility: The capability of a UXV to move from place to place, while under any method of control, in order to accomplish its mission or function.

Mode of control (also control mode): The manner by which a UXV receives instructions that govern its actions. Examples are remote control, semi autonomous, etc.

Modularity: The property of flexibility built into a system by designing discrete units (hardware and software) that can easily be joined to or interface with other parts or units.

Navigation: The process whereby a UXV makes its way along a route that it planned, that was planned for it or, in the case of teleoperation, that a human operator sends it in real time.

Negative obstacles: A terrain feature that presents a negative deflection relative to the horizontal plane of the UGV such that it prevents the UXV continuation on an original path. Examples are depressions, canyons, creek beds, ditches, bomb craters, etc.

Non-line-of-sight: (1) Visually, a condition that exists when there is an obstruction between the viewer and the object being viewed. (2) In radio frequency communications, a condition that exists when there is an intervening object, such as dense vegetation, terrain, man-made structures or the curvature of the earth, between the transmit and receive antennas, and transmission and reception would be impeded. Non-line-of-sight communications implies communications across this normally non-line-of-sight terrain/distance. An intermediate ground, air, surface or space-based retransmission capability may be used to remedy this condition.

Obstacle avoidance: The action of a UXV when it takes a path around a natural or man-made obstruction that prevents continuation on its original path.

Obstacle detection: The capability of a UXV or its operator to determine that there is an obstruction, natural or man-made, positive or negative, in its path.

Obstacle negotiation: The capability of a UXV or its operator to navigate through or over an obstacle once it's detected and characterized as negotiable.

Operator Control Unit (OCU): The computer(s), accessories and data link equipment that an operator uses to control, communicate with, receive data and information from, and plan missions for one or more UXVs.

Payload: The load (expressed in pounds of equipment, gallons of liquid or other cargo) which the UXV is designed to transport under specified conditions, in addition to its unladen weight.

Perception: Transformation of sensor signals into knowledge about situations and events in the real world.

Plug-and-play: The ability to quickly remove one type of mission module from a UXV and replace it with another type, the new mission module being ready for immediate use.

Remote Control: A mode of control of a UXV wherein the human operator, without the benefit of video feedback, directly controls on a continuous basis the actions of the UXV using visual line-of-sight cues.

Retro-traverse: A behaviour of a UXV in which, having recorded the navigation data on where it has been, it autonomously retraces its route to a point where it can continue its mission.

Robot: A machine or device that works automatically or operates by remote control.

Robotics: The study and techniques involved in designing, building and using robots.

Semi-autonomous: A mode of control of a UXV wherein the human operator plans a mission for the UXV which then conducts the assigned mission; the UXV requires only infrequent human intervention when it needs further instructions.

Situation: A set of relationships existing between entities in the real world.

Situational awareness: A situated creature or robot is one that is embedded in the world and does not deal with abstract descriptions but, through its sensors with the here and now of the world, can directly influence its behaviour.

Telepresence: The capability of a UXV to provide the human operator, using video and/or other cues, with feedback which the operator can use to control, on a continuous basis, the actions of the UXV.

Tether: A fiber optic or other communications cable that connects the OCU to the UXV platform.

Unmanned Air Vehicle (UAV): A powered, mobile, airborne conveyance that does not have a human aboard; can be operated in one or more modes of control (autonomous, semi-autonomous, teleoperation, remote control); can be expandable or recoverable; and can have lethal or non-lethal mission modules.

Unmanned Cyber Vehicle (UCV): UCVs are also known as Autonomous Agents and can be defined as "computational systems that inhabit some complex dynamic environment, sense and act autonomously in this environment, and by doing so realize a set of goals or tasks for which they are designed." [fromMaes, Pattie (1995), "Artificial Life Meets Entertainment: Life like Autonomous Agents," *Communications of the ACM*, 38, 11, 108-114]

Unmanned Ground Vehicle (UGV): A powered, mobile, ground conveyance that does not have a human aboard; can be operated in one or more modes of control (autonomous, semi-autonomous, teleoperation, remote control); can be expandable or recoverable; and can have lethal or non-lethal mission modules.

Unmanned Orbital Vehicle (UOV): A powered, mobile, space conveyance that does not have a human aboard; can be operated in one or more modes of control (autonomous, semi-autonomous, teleoperation, remote control); can be expandable or recoverable; and can have lethal or non-lethal mission modules.

Unmanned Surface Vehicle (USV): A powered, mobile, water surface conveyance that does not have a human aboard; can be operated in one or more modes of control (autonomous, semi-autonomous, teleoperation, remote control); can be expandable or recoverable; and can have lethal or non-lethal mission modules.

Unmanned Underwater Vehicle (UUV): A powered, mobile, underwater conveyance that does not have a human aboard; can be operated in one or more modes of control (autonomous, semi-autonomous, teleoperation, remote control); can be expandable or recoverable; and can have lethal or non-lethal mission modules.

Unmanned Systems: A grouping of military systems, the common characteristic being that there is no human operator aboard. May be mobile or stationary. Includes categories of unmanned ground vehicles (UGV), unmanned aerial vehicles (UAV), unmanned underwater vehicles (UUV), unmanned munitions (UM) and unattended ground sensors (UGS). Missiles, rockets and their sub-munitions, and artillery are not considered unmanned systems.

UXV: the class of unmanned systems representing the unmanned vehicles.

Windowing or Masking: Selects the regions of space and/or time to be considered.

Waypoints: Intermediate locations through which a UXV must pass en route to a particular destination.

Waypoint navigation: The process whereby a UXV makes its way along a route of planned waypoints that it planned or were planned for it.

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Appendix A
Existing Cyberbots

Name	Purpose	Availability	Platform
Acme.Spider	indexing maintenance statistics	source	Java
Ahoy! The Homepage Finder	maintenance	none	UNIX
Alkaline	indexing	binary	UNIX, Windows95 WindowsNT
Anthill	indexing	not yet	independent
Walhello appie	indexing	none	Windows98
Arachnophilia			
Arale	maintenance	source, binary	UNIX, Windows, Windows95, WindowsNT, os2, Mac, Linux
Araneo	indexing, statistics	none	Linux
ArchitextSpider	indexing, statistics		
Aretha			Macintosh
ARIADNE	statistics, development of focussed crawling strategies	none	Java
arks	indexing	data	PLATFORM INDEPENDENT
ASpider (Associative Spider)	indexing		UNIX
ATN Worldwide	indexing		
Atomz.com Search Robot	indexing	service	UNIX
AURESYS	indexing, statistics	protected by password	Aix, UNIX
BackRub	indexing, statistics		
unnamed	Copyright Infringement Tracking	24/7	NT
Big Brother	maintenance	binary	Mac
Bjaaland	indexing		UNIX
BlackWidow	indexing, statistics		
Die Blinde Kuh	indexing		UNIX
Bloodhound	Web site download	executable	Windows95, WindowsNT, Windows98, Windows2000
Borg-Bot	indexing, statistics		Linux, Windows2000
bright.net caching robot	caching		
BSpider	indexing		UNIX
CACTVS Chemistry Spider	indexing		
Calif	indexing		UNIX
Cassandra	indexing		cross-platform
Digimarc Marcspider/CGI	maintenance		WindowsNT
Checkbot	maintenance	source	UNIX,WindowsNT
ChristCrawler.com	indexing		Windows NT 4.0 SP5
churl	maintenance		
cIeNcIaFiCcIoN.nEt	indexing		Linux

Name	Purpose	Availability	Platform
CMC/0.01	maintenance		UNIX
Collective	Collective is a highly configurable program designed to interrogate on-line search engines and on-line databases; • it will ignore Web pages that lie about their content and will also ignore dead URLs; • it can be extremely strict; • it searches each Web page it finds for your search terms to ensure those terms are present; • any positive URLs are added to an HTML file for you to view at any time, even before the program has finished; • it can wander the Web for days, if required.	executable	Windows95, WindowsNT, Windows98, Windows2000
Combine System	indexing	source	UNIX
Conceptbot	indexing	data	UNIX
CoolBot	indexing		UNIX
Web Core / Roots	indexing, maintenance		
XYLEME Robot	indexing	data	UNIX
Internet Cruiser Robot	indexing		UNIX
Cusco	indexing		any
CyberSpyder Link Test	link validation, some HTML validation	binary	Windows 3.1x, Windows95, WindowsNT
DeWeb(c) Katalog/Index	indexing, mirroring, statistics		
DienstSpider	indexing		UNIX
Digger	indexing		UNIX, Windows
Digital Integrity Robot	WWW indexing		UNIX
Direct Hit Grabber	indexing and statistics		UNIX
DNAbot	indexing	data	UNIX, Windows, Windows95, WindowsNT, Mac
DownLoad Express	graphic download	binary	Windows95/98/NT
DragonBot	indexing		WindowsNT
DWCP (Dridus' Web Cataloging Project)	indexing, statistics	source, binary, data	Java
e-collector	e-mail collector	binary	Windows 9*/NT/2000
EbiNess	statistics	Open Source	UNIX (Linux)
EIT Link Verifier Robot	maintenance		
ELFINBOT	indexing for the Let's Find It Now search engine		UNIX
Emacs-w3 Search Engine	indexing		
ananzi	indexing		
Esther	indexing	data	UNIX (FreeBSD

Name	Purpose	Availability	Platform
			2.2.8)
Evliya Celebi	indexing, Turkish content	source	UNIX
nzexplorer	indexing, statistics	source (commercial)	UNIX
FastCrawler	indexing		Windows 2000 Adv. Server
Fluid Dynamics Search Engine robot	indexing	Source, data	UNIX, windows
Felix IDE	indexing, statistics	binary	Windows95, WindowsNT
Wild Ferret Web Hopper #1, #2, #3	indexing, maintenance, statistics		
FetchRover	maintenance, statistics	binary, source	Windows/NT, Windows/95, Solaris SPARC
fido	indexing		UNIX
Hämähäkki	indexing		UNIX
KIT-Fireball	indexing		UNIX
Fish search	indexing	binary	
Fouineur	indexing, statistics		UNIX, Windows
Robot Francoroute	indexing, mirroring, statistics		
Freecrawl	indexing		UNIX
FunnelWeb	indexing, statistics		
gammaSpider, FocussedCrawler	indexing, maintenance		UNIX, Windows, Windows95, WindowsNT, Linux
gazz	statistics		Unix
GCreep	indexing		linux+mysql
GetBot	maintenance		
GetURL	maintenance, mirroring		
Golem	maintenance		Mac
Googlebot	indexing		Linux
Grapnel/0.01 Experiment	indexing	none yet	WinNT
Griffon	indexing		UNIX
Gromit	indexing		UNIX
Northern Light Gulliver	indexing		UNIX
Gulper Bot	indexing		Linux
HamBot	indexing		UNIX, Windows95
Harvest	indexing		
havIndex	indexing	binary	Java VM 1.1
HI (HTML Index) Search	indexing		
Hometown Spider Pro	indexing		WindowsNT
Wired Digital	indexing		UNIX
ht://Dig	indexing	source	UNIX
HTMLgobble	mirror		
Hyper-Decontextualizer	indexing		
iajaBot	indexing		UNIX, Windows
IBM_Planetwide	indexing, maintenance, mirroring		
Popular Iconoclast	statistics	source	UNIX (OpenBSD)
Ingrid	indexing	commercial, as part of search engine package	UNIX

Name	Purpose	Availability	Platform
Imagelock	maintenance		Windows95
IncyWincy			
Informant	indexing		UNIX
InfoSeek Robot 1.0			
Infoseek Sidewinder	indexing		
InfoSpiders	search		UNIX, Mac
Inspector Web	maintenance: link validation, HTML validation, image size validation, etc.	free service and more extensive commercial service	UNIX
IntelliAgent	indexing		
I, Robot	indexing		UNIX
Iron33	indexing, statistics	source	UNIX
Israeli-search	indexing		
JavaBee	Stealing Java Code	binary	Java
JBot Java Web Robot	indexing	source	Java
JCrawler	indexing		UNIX
AskJeeves	indexing, maintenance		Linux
JoBo Java Web Robot	downloading, mirroring, indexing	source	UNIX, Windows OS/2, Mac
Jobot	stand-alone		
JoeBot			
The Jubii Indexing Robot	indexing, maintenance		
JumpStation	indexing		
image.kapsi.net	indexing	data	UNIX
Katipo	maintenance	binary	Macintosh
KDD-Explorer	indexing		UNIX
Kilroy	indexing, statistics		UNIX, WindowsNT
KO_Yappo_Robot	indexing		UNIX
LabelGrabber	Grabs PICS labels from Web pages, submits them to a label bureau	source	Windows, Windows95, WindowsNT, UNIX
larbin	Your imagination is the only limit	source (GPL), mail me for customization	Linux
legs	indexing		Linux
Link Validator	maintenance		UNIX, Windows
LinkScan	Link checker, SiteMapper, and HTML Validator	Program is shareware	UNIX, Linux, Windows 98/NT
LinkWalker	maintenance, statistics		WindowsNT
Lockon	indexing		UNIX
logo.gif Crawler	indexing		UNIX
Lycos	indexing		
Mac WWWWorm	indexing		Macintosh
Magpie	indexing, statistics		UNIX
marvin/infoseek	indexing		UNIX
Mattie	Procurement Spider		UNIX
MediaFox	indexing and maintenance		Java
MerzScope	Web-mapping	binary	(Java Based) UNIX,Windows95, WindowsNT, OS2, Mac, etc.
NEC-MeshExplorer	indexing		UNIX

Name	Purpose	Availability	Platform
MindCrawler	indexing		Linux
mnoGoSearch search engine software	indexing	source	UNIX, Windows, Mac
moget	indexing, statistics		UNIX
MOMspider	maintenance, statistics	source	UNIX
Monster	maintenance, mirroring	binary	UNIX (Linux)
Motor	indexing	data	Mac
Muncher	indexing		UNIX
Muscat Ferret	indexing		UNIX
Mwd.Search	indexing		UNIX (Linux)
Internet Shinchakubin	find new links and change pages	binary as bundled software	Windows98
NetCarta WebMap Engine	indexing, maintenance, mirroring, statistics		
NetMechanic	Link and HTML validation	via Web page	UNIX
NetScoop	indexing		UNIX
newscan-on-line	indexing	binary	Linux
NHSE Web Forager	indexing		
Nomad	indexing		
The NorthStar Robot	indexing		
Occam	indexing		UNIX
HKU WWW Octopus	indexing		
Openfind data gatherer	indexing		
Orb Search	indexing	data	UNIX
Pack Rat	both maintenance and mirroring		UNIX
PageBoy	indexing		UNIX
ParaSite	indexing		WindowsNT
Patric	statistics	data	UNIX
pegasus	indexing	source, binary	UNIX
The Peregrinator			
PerlCrawler 1.0	indexing	source	UNIX
Phantom	indexing		Macintosh
PhpDig	indexing	source	Apache/php/mysql
PiltdownMan	statistics		Windows95, Windows98, WindowsNT
Pimptrain.com's robot	indexing	source, data	UNIX
Pioneer	indexing, statistics		
HTML_analyzer	maintenance		
Portal Juice Spider	indexing, statistics		UNIX
PGP Key Agent	indexing		UNIX, Windows NT
PlumtreeWebAccessor	indexing for the Plumtree Server		WindowsNT
Poppi	indexing		UNIX/Linux
PortalB Spider	indexing		UNIX
psbot	indexing		Linux
GetterroboPlus Puu	Data, maintenance: link validation		UNIX
The Python Robot			
Raven Search	Indexing: gather content for commercial query engine		Unix, Windows98, WindowsNT, Windows2000

Name	Purpose	Availability	Platform
RBSE Spider	indexing, statistics		
Resume Robot	indexing		
RoadHouse Crawling System			
Road Runner: The ImageScape Robot	indexing		UNIX
Robbie the Robot	indexing		UNIX, windows95, windowsNT
ComputingSite Robi/1.0	indexing, maintenance		UNIX
RoboCrawl Spider	indexing		Linux
RoboFox	site download		Windows9x, Windowsme, WindowsNT4, Windows2000
Robozilla	maintenance		
Roverbot	indexing		
RuLeS	indexing		UNIX
SafetyNet Robot	indexing		
Scooter	indexing		UNIX
Search.Aus-AU.COM	indexing: gather content		Mac, UNIX, Wwindows95, WwindowsNT
Sleek	indexing	source, data	UNIX, Linux, Windows
SearchProcess	Statistic		Linux
Senrigan	indexing		Java
SG-Scout	indexing		
ShagSeeker	indexing	data	UNIX
Shai'Hulud	mirroring	source	UNIX
Sift	indexing	data	UNIX
Simmany Robot Ver1.0	indexing, maintenance, statistics		UNIX
Site Valet	maintenance	data	UNIX
Open Text Index Robot	indexing		UNIX
SiteTech-Rover	indexing		
Skymob.com	indexing		UNIX
SLCrawler	to build the site map		Windows, Windows95, WindowsNT
Inktomi Slurp	indexing, statistics		UNIX
Smart Spider	indexing	data, binary, source	Windows95, WindowsNT
Snooper			
Solbot	indexing		UNIX
Speedy Spider	indexing		Windows
spider_monkey	indexing	data	UNIX
SpiderBot	indexing, mirroring	source, binary, data	UNIX, Windows, Windows95, WindowsNT
Spiderline Crawler	indexing	free and commercial services	UNIX
SpiderMan	user searching using IR	binary and source	Java 1.2

Name	Purpose	Availability	Platform
	technique		
SpiderView(tm)	maintenance	source	UNIX, nt
Spry Wizard Robot	indexing		
Site Searcher	indexing	binary	winows95, windows98, windowsNT
Suke	indexing	source	FreeBSD3.*
suntek search engine	search portal on Asian web sites		NT, Linux, UNIX
Sven	indexing		Windows
TACH Black Widow	maintenance: link validation		UNIX, Linux
Tarantula	indexing		UNIX
tarspider	mirroring		
Tcl W3 Robot	maintenance, statistics		
TechBOT	statistics, maintenance		UNIX
Templeton	mirroring, mapping, automating web applications	binary	OS/2, Linux, SunOS, Solaris
TitIn	indexing, statistics	data, source on request	UNIX
TITAN	indexing		SunOS 4.1.4
The TkWWW Robot	indexing		
TLSpider	indexing		Linux
UCSD Crawl	indexing, statistics		
UdmSearch	indexing, validation	source, binary	UNIX
URL Check	maintenance	binary	UNIX
URL Spider Pro	indexing	binary	Windows9x/NT
Valkyrie	indexing		UNIX
Verticrawl	indexing, maintenance, statistics, and classifying URLs		UNIX, Linux and WindowsNT
Victoria	maintenance		UNIX
vision-search	indexing		
Voyager	indexing, maintenance		UNIX
VWbot	indexing	source	UNIX
The NWI Robot	discovery, statistics		UNIX
W3M2	indexing, maintenance, statistics		
WallPaper	picture download, indexing, gathering	binary/source	Win32
the World Wide Web Wanderer	statistics	data	UNIX
w@pSpider by wap4.com	indexing, maintenance	data	UNIX
WebBandit Web Spider	Resource Gathering / Server Benchmarking	source, binary	windows95
WebCatcher	indexing		UNIX, Windows, Mac
WebCopy	mirroring		
webfetcher	mirroring		
The Webfoot Robot			
weblayers	maintenance		
WebLinker	maintenance		
WebMirror	mirroring		Windows95
The Web Moose	statistics, maintenance	data	Windows NT

Name	Purpose	Availability	Platform
WebQuest	indexing		UNIX
Digimarc MarcSpider	maintenance		WindowsNT
WebReaper	indexing/offline browsing	binary	Windows95, WindowsNT
webs	statistics		UNIX
Websnarf			
WebSpider	maintenance, link diagnostics		
WebVac	mirroring		
webwalk		indexing, maintenance, mirroring, statistics	
WebWalker	maintenance	source	UNIX
WebWatch	maintenance, statistics		
Wget	mirroring, maintenance	source	UNIX
whatUseek Winona	Robot used for site-level search and meta-search engines		UNIX
WhoWhere Robot	indexing		Sun UNIX
Weblog Monitor	statistics	source, data	UNIX, Windows,
w3mir	mirroring.		UNIX, WindowsNT
WebStolperer	indexing		UNIX, NT
The Web Wombat	indexing, statistics.		
The World Wide Web Worm	indexing		
WWWC Ver 0.2.5	maintenance	binary	Windows, Windows95, WindowsNT
WebZinger	indexing	binary	Windows95, WindowsNT 4, Mac, Solaris, UNIX
XGET	mirroring	binary	X68000, X68030
Nederland.zoek	indexing		UNIX (Linux)

Appendix B

The template and example presented in this Appendix is derived from DRDC's Technology Watch program. This approach is driven by a process of understanding outcomes and requirements, convergence and innovation issues, maturity and time frames, niche applications, partnering, and economic benefit. As such, the flow of this process is as follows:

- State *desired outcomes* for CF/DND (and their relevance to certain parts of CF/DND)
- Review *convergence issues*. Look at:
    - technology factors
    - process factors
    - infrastructure factors
- Define whether technology is *disruptive* or *sustaining*. Consider changes in:
    - business model
    - performance metrics
    - incubating users
- Review *technology/system factors* (innovation type: incremental, architectural, modular, or radical)
- *Maturity* considerations and *Technology Readiness Level (TRL)*
- Alignment with *CF/DND requirements* (desired outcomes align with organizational requirements)
- Discuss *Canadian niche* implications, if applicable
- Discuss *alliance/partnering* potential, if applicable
- Perform *economic benefit* calculation, if applicable
- Provide/present *advisory input* (upon which decision-makers can base recommendations).

The intent of this Appendix is to provide the reader with a methodology for analyzing UXVs within the context of desired outcomes and requirements.

For more information on this methodology, see:
S. MacKenzie, A. Chong, T. Romet, and K. Thomas, **NBIC Disruptive Technology Watch**,*Defence Research and Development Canada*,2003.

Technology under Consideration: MILITARY TACTICAL BEHAVIOUR

Description: In order for a fully autonomous vehicle to participate in missions, particularly covert or hunter/killer type missions, the vehicle must be able to behave in an appropriate fashion. This will be a software system that will incorporate mission specific behaviour into the overall mission planning and task execution portion of the autonomous functionality.

Status: Early work on incorporating behaviour models into a robots task planning and activities have shown great promise. Early work has involved creating systems that emulate human characteristics in social interactions.

Background: The requirement for military behaviour has been identified but very little effort has been focussed on military behaviour.

Opportunity: Develop a behaviour-based control system which can provide input to the general planning system of autonomous vehicles and for which new behaviour models can be downloaded to the vehicle depending on the mission. Use of learning and adopting techniques would significantly enhance the usability of this technology.

Desired Outcomes for CF: A software module capable of providing military tactical input to the autonomous planning system.

Convergences Issues:

Technology Factors: Inference engines, neural networks, genetic algorithms, adaptive algorithms, etc.

Process Factors: Processing speed, memory

Infrastructures Factors: Secure software maintenance, upgrade, and tamper-proof capability (authentication, integrity)

Define whether technology is disruptive or sustaining: Disruptive

Business Model: Significantly changes the scope of tasks available to autonomous vehicles in a military action.

Performance Metrics: Depth of knowledge, adaptability, measures for out-of-bounds capability (i.e., machine is beyond its capabilities)

Potential incubating users and uses: JTF2

Technology/System factors (incremental, architectural, modular, radical): Modular – introduces an expendable, stealthy, tool to augment military actions.

Maturity considerations and TRL: The tools techniques and concepts for how such a system would be developed are still very immature TRL = 2.

Current Players: Many of the Canadian universities could provide experts to work in this area – but the military application is very nascent.

Alignment of outcomes with CF requirements: Good alignment – augments forces in harms way while providing potential for removing the human from harms way.

Canadian niche implications: Technology fits within the Canadian capabilities in AI, planning and learning systems.

Alliance/partnering potential: Opportunity to partner with US, British efforts to provide a core module to autonomous vehicles.

Advisory input: The CF needs to fund this activity as it is outside of the demands of commercial or other government department needs. Although an engine that enables specific task knowledge to be stored and then used to direct the planning could have non-military uses, the immediate need to push this technology in this direction will be some years off for commercial applications.

Appendix C[63]
NSERC Strategic Assessment of University Research Capabilities and Direction 2002

Computing and Information Sciences

A Vision for the Discipline in Canada

NSERCS vision for Computing and Information Sciences (CIS) in Canada is bold. It consists of two key elements.

1. *The Canadian CIS community will continue to be a world leader in discipline-based research.*
   First, our vision requires that we continue to be a world leader in CIS research, where leadership is defined both by traditional discipline-based measures of scholarly activity and by the significance and impact of our innovations in the broader community. Our vision of discipline-based research encompasses both core research within key sub-areas of the field and intra-disciplinary research that spans internal, sub-discipline boundaries.

2. *The Canadian CIS community will lead inter-disciplinary research and be a catalyst for research in many disciplines.*
   Second, our vision is to enhance the leadership role we play in research collaborations across a focussed range of disciplines where we clearly identify the potential for revolutionary impact. As well, we will help to address CIS problems that arise in research in many disciplines.

State of the Discipline in Canada

Canada is, and has been for many years, remarkably strong in theoretical computer science and in theoretical aspects of other sub-areas of the discipline, including artificial intelligence (AI), databases and scientific computation. This strength is due, in part, to the fact that theoretical work is relatively inexpensive to do and, once done, is relatively easy to evaluate. Outstanding researchers in theory are easy to identify, especially at the early stages of their academic careers.

Overall, Canada is not as strong in experimental computer science. This lack of strength is due, in part, to our inability to articulate (among ourselves, to our university administrations and to our funders) the distinction between experimental computer science and applied computer science. Experimental work is not applied work in our discipline any more than it is in other areas of science such as physics and chemistry. Experiments in CIS often are required to explore fundamental ideas. A prototype system is designed, built and tested empirically to evaluate the strengths and weaknesses of a new idea or approach. Successful research prototypes become platforms for future research. Experimental work in CIS requires significant infrastructure and thus tends to be more expensive to do and more difficult to evaluate (at least in the short term). When not funded adequately and for a sufficient period of time, weakness in experimental work becomes a self-fulfilling prophecy.

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[63] Portions of the NSERC Strategic Assessment of University Research Capabilities and Direction 2002

Canadian CIS researchers also interact with industry. Problems of interest to industry help to motivate academic research. At the same time, industry interaction can facilitate commercialization of university-based research. In general, the established Canadian ICT industry welcomes collaboration with university researchers to facilitate the development and deployment of its own technologies. It should be noted, however, that companies in Canada spend far less on R&D than they do in the US or in Europe.

Strengths of Canadian CIS Research

Canada has world-class researchers and research groups in many key areas of computing and information sciences (CIS). Indeed there are some significant areas where the very roots of the subject go back to pioneering Canadian work. Canada's population base is roughly one-tenth that of the US and roughly half of that of the UK. Thus, to an outsider, the overall depth and strength of the discipline in Canada may come as somewhat of a surprise. Below, we highlight senior researchers noted for particular strengths in their areas, as well as some outstanding junior researchers. A major feature and strength of the discipline is that it is a young, extremely dynamic subject, with many researchers working effectively in several areas simultaneously. People in the discipline also take a leadership role in inter-disciplinary endeavours. Section 1.3 describes new areas and inter-disciplinary activities that are emerging from Canada's traditional areas of excellence.

Theory of Computation

Theory of computation is one of our strongest areas, containing some of the world's top researchers in logic and complexity theory, algorithms, computational geometry, probabilistic algorithms and related areas.

5. *Complexity Theory and Algorithms*. Toronto has a distinguished complexity theory group that includes Stephen Cook, one of the founders of the modern subject of computational complexity. Cook currently works in logic and complexity. The Toronto group also includes Allan Borodin (complexity theory, network routing and algebraic computation). There are several other strong groups in algorithms and complexity. The Waterloo group is more applied and includes Ian Munro (data structures), Prabhakar Ragde (complexity and algorithms) and Douglas Stinson (cryptography). UBC has several leading researchers in complexity including Nick Pippenger and Anne Condon. Pippenger is perhaps best known for his work on parallel complexity classes. Luc Devroye (McGill) works in probabilistic analysis and in computational geometry.
6. *Computational Geometry*. Computational geometry is a particular strength in Canada, with people of international stature, including David Avis (McGill), Godfried Toussaint (McGill), Luc Devroye (McGill) and David Kirkpatrick (UBC). Carleton's Computational Geometry Group includes leading senior researchers Frank Dehne and Jörg Sack and junior researcher Prosenjit Bose.

7. *Logic and Computation*. Canada has a small but distinguished presence in logic and computing. In logics and complexity theory, researchers such as Stephen Cook (Toronto) and Denis Thérien (McGill) are among the strongest. In AI, logic is a fundamental tool for knowledge representation and reasoning. Many of Canada's top AI researchers also are leaders in logics for AI. In the areas of logic and programming language semantics, concurrency and type systems (mainstream European theory), Canada has a small but distinguished group of researchers. These include Prakash Panangaden (McGill) and Phil Scott (Ottawa). Leonid Libkin (Toronto) is a leader in logics and database theory. Helmut Jurgensen (UWO) excels in formal languages and automata theory.
8. *Quantum Computing and Quantum Cryptography*. Canada has great strength in this emerging field, out of proportion to its size. Gilles Brassard (Montreal), the holder of the largest research grant in GSCs 330/331, is one of the founders of quantum cryptography. His research group in Montreal is an important attractor for scientists from around the world. Claude Crepeau (McGill) is another well-known researcher in quantum computing. Michele Mosca (Waterloo) and John Watrous (Calgary) are strong junior researchers. Nick Pippenger (UBC) now also is involved in theoretical aspects of quantum computation.

Artificial Intelligence

Canada has an outstanding international reputation in artificial intelligence (AI). Canadian AI researchers have earned the discipline's highest honours. Hector Levesque (Toronto) is one of eighteen winners (since 1971) of the International Joint Conferences on Artificial Intelligence (IJCAI) Computers and Thought award. Ray Reiter (Toronto) is one of eight winners (since 1985) of the IJCAI Award for Research Excellence. The American Association for Artificial Intelligence (AAAI) Fellows program was started in 1990. There are 5-10 new Fellows selected each year. Canadian AAAI Fellows include: Geoff Hinton (Toronto), Hector Levesque (Toronto), Alan Mackworth (UBC), Ray Reiter (Toronto), Mark Fox (Toronto), John Mylopoulos (Toronto), David Poole (UBC) and Jonathan Schaeffer (Alberta). AI is a major scientific resource in Canadian computer science. Among the world-class AI groups in Canada, the group at Toronto is not merely worldclass but world renowned. There also are very strong groups at UBC and Alberta. Many of the top Canadian AI researchers excel in more than one sub-area in the discipline. Here are representative examples:

1. *Knowledge Representation and Reasoning*. Canada is fortunate to have some of the world's top stars in knowledge representation, including Ray Reiter, (Toronto), Alan Mackworth (UBC) and Hector Levesque (Toronto). John Mylopoulos (Toronto) is a leader in knowledge-based systems who currently works in information system design and software engineering. Canada also has excellent researchers in probabilistic reasoning, decision-making under uncertainty and Bayesian network theory. Some of the leading names are David Poole (UBC), Craig Boutilier (Toronto) and Fahiem Bacchus (Toronto). Leaders in computational linguistics and natural language understanding include Nick Cercone (Waterloo) and Graeme Hirst (Toronto).
2. *Computer Vision*. Canada has a remarkable tradition of strength and leadership in computer vision. Among the leading senior researchers are: Allan Jepson (Toronto) in

visual inferencing, John Tsotsos (York) in visual attention, David Lowe (UBC) in object recognition, Jim Clark (McGill) in active vision, Jim Little (UBC) in real-time vision, Brian Funt (SFU) in colour vision and Bob Woodham (UBC) in physics-based vision. There are other younger researchers. The continuity of researchers at all levels suggests that computer vision will remain strong for some time to come. There also are leading researchers in the related areas of pattern recognition and image and signal processing, including Ching Suen (character recognition) and Adam Krzyzak (pattern recognition and neural nets), both at Concordia, XiaolinWu (image compression) at UWO and Tom Luo (signal processing for communications) at McMaster. Luc Devroye (McGill) and Godfried Toussaint (McGill) both contribute to theoretical work in pattern recognition.

3. *Robotics*. Robotics also is well-represented in Canada. In the CIS community, there are established groups at UBC, Toronto and York. There are emerging stars such as Greg Dudek (McGill). There also is the remarkable work of Randy Ellis (Queen's) on computer-enhanced robotic surgery. The overall youth of our robotics researchers suggests that this area could remain one of Canada's strengths for a long time, provided that the experimental nature of the research is adequately supported.
4. *Machine Learning and Neural Networks*. Machine learning is a rapidly growing field with lots of synergy between AI researchers and complexity theorists. Geoff Hinton, (Toronto) is the world leader in neural networks. Russ Greiner (Alberta) works on learning and effective performance systems. Among the notable more junior people working on neural networks is Yoshua Bengio (Montr´eal).
5. *Search and Game Playing*. Holger Hoos (UBC) solves combinatorial problems using stochastic local search. His Ph.D. thesis was selected by the national German Computer Society as the best German Ph.D. thesis in all of Computer Science for the year 1998. Computer games may be regarded as a specialized subfield of search. Canada has a major player in Jonathan Schaeffer (Alberta). Schaeffer is the author of the program Chinook, the World Man-Machine Checkers Champion.

Computational Mathematics

Canada has international strength in several areas of computational mathematics funded by GSCs 330/331. The roots of modern algorithmic combinatorics are in Canada, dating from the 1950s and early 1960s. Waterloo remains a leader in this area.

1. *Symbolic Computation*. Canada has special strength in symbolic computation. Maple (Waterloo Maple Corporation) was developed by Canadian CIS researchers. Maple is a widely used software tool. Maple also remains a valued platform for continuing research in symbolic computation. Among the leading Canadian researchers in the area, we mention George Labahn and Keith Geddes (Waterloo). There also are active symbolic computation groups at UWO and at SFU.
2. *Discrete Applied Mathematics*. Canada has a strong tradition of producing excellent graph theorists and combinatorialists. Among the world-class experts in graph theory, graph algorithms and related areas of discrete applied mathematics we include Bruce Reed (McGill), Pavol Hell (SFU) and Derek Corneil (Toronto).
3. *Scientific Computation*. Scientific computation includes numerical methods for the solution of partial differential equations, applied linear algebra and the development of reliable software packages. Among our top senior scientists, we include: Uri

Ascher (UBC), Alan George (Waterloo), Bob Russell (SFU), Wayne Enright (Toronto), Peter Forsyth (Toronto), Joseph Liu (York), Ken Jackson (Toronto) and Eusebius Doedel (Concordia).

Computer Graphics

Computer graphics is a Canadian strength dating back to pioneering work done at the National Film Board. The graphics community has won many professional awards, is well respected, and (regrettably from the perspective of faculty retention) is in great demand. Canadian graphics specialists have contributed to such Hollywood movies as Alien and Pixar's *Toy Story*. Senior researchers Przemyslaw Prusinkiewicz and Brian Wyvill are at Calgary. Prusinkiewicz received the 1997 ACM SIGGRAPH Computer Graphics Achievement Award for his cutting-edge work in modeling and visualizing biological structures. Eugene Fiume (Toronto) leads the Dynamic Graphics Project. Fiume was Papers Chair of SIGGRAPH 2001. Kellogg Booth is the senior leader of the UBC Imager graphics group. Michiel van de Panne joins the group January, 2002. UBC also has three other new, outstanding junior faculty in graphics and HCI. There are strong emerging graphics research groups also at Waterloo and at the Université de Montreal.

Human Computer Interaction

Human Computer Interaction (HCI) deals with theoretical, experimental and applied aspects of how people interact with the systems we build. Once an offshoot of computer graphics, HCI has expanded to encompass a wide range of interaction modalities and a wide range of potential applications. For example, HCI is now seen as an essential component of software engineering. HCI is inherently inter-disciplinary since it depends on models of human performance as well as on knowledge of hardware and software design. Experimental work in HCI typically includes experimental research with human subjects.

Leading HCI researchers include Kellogg Booth (UBC), Bill Cowan (Waterloo) and Saul Greenberg (Calgary). Carl Gutwin (Saskatchewan) is emerging as a leader in the usability of real-time distributed groupware. HCI is a growth area in CIS. This is a positive trend that will continue as computers become more ubiquitous, pervasive and tangible (see Section 1.3.2).

Database Systems

Canada has significant strength in databases with senior researchers playing leading roles across a wide range of core topics and new applications including the web, XML data, multimedia and e-commerce. Alberto Mendelzon (Toronto) works in database theory, data languages and knowledge base management. Frank Tompa (Waterloo) is a world leader in the area of structured text management. Raymond Ng (UBC) is an emerging star in the field of knowledge discovery and data mining. Tamer ¨ Ozsu (Waterloo) works in distributed data and object management, multimedia data management and e-commerce. In July, 2001, ¨ Ozsu was elected to a two-year term as Chair of ACM SIGMOD. Recently, databases also has been an area of successful faculty recruitment. Several universities report new junior appointments with outstanding potential. Two notable recent appointments are Ren´ee Miller and Leonid Libkin, both at Toronto. Miller received a US Presidential Early Career Award for Scientists and Engineers (PECASE) in 1997. This is the highest honour bestowed by the US government on outstanding scientists and engineers beginning their careers. Libkin previously was at Bell Labs and is a world leader in the application of mathematical logic to databases.

The database community has significant interaction with the Canadian database software industry. Prominent examples include Open Text Corporation in Waterloo, the IBM DB2 development group in Toronto, iAnywhere Solutions in Waterloo, Bell University Labs and Nortel.

Other Systems Areas
Systems includes all aspects of the performance of computer systems, such as operating systems, networks, performance analysis, hardware specification and testing, programming languages and compiler design.

1. *Operating Systems, Networks and Performance Analysis*. Canada's outstanding senior researchers include Ken Sevcik (Toronto) in performance analysis and information distillation, MurrayWoodside (Carleton) in software performance engineering, JohnnyWong (Waterloo) in performance evaluation of computer communications networks, Michael Stumm (Toronto) in multiprocessor operating systems and Derek Eager (Saskatchewan) in performance evaluation of distributed and parallel systems. In July, 2001, Eager was elected to a two-year term as Chair of ACM SIGMETRICS. Mike Feeley (UBC) is an emerging star in scalable and adaptable distributed systems. Finally, Vassos Hadzilacos, Faith Fich and Sam Toueg (Toronto) are a strong group in the theory of distributed computing. Toueg is a recent senior appointment. Previously he was at Cornell.
2. *Hardware Specification and Testing*. Senior researchers are Eduard Cerny (Montreal) in the specification, verification and synthesis of microelectronics systems and Jon Muzio (UVic) in the design and analysis of testing methods for digital circuits. Mark Greenstreet (UBC) works in hybrid systems on verification using continuous models.
3. Programming Languages and Compilers. In the area of compiler design, Laurie Hendren (McGill) is a pioneer in analysis of pointer-based programs. She is Program Chair for the 2002 Programming Language Design and Implementation (PLDI) conference. Nigel Horspool (UVic) works on compilers and programming language implementation, currently doing profile-based code motion optimization. Gregor Kiczales (UBC) is a new senior appointment. He introduced the idea of aspect-oriented programming to explore programming language mechanisms that allow functionality to crosscut boundaries of a program's traditional modular design.

Software Engineering
The CIS community considers software engineering to be a core sub-discipline of CIS. Indeed, computer science researchers originally coined the term and have been the dominant force defining the field for more than 30 years. Software engineering also is the subject of a joint submission with the Electrical and Computer Engineering (ECE). We do not repeat here the case presented in the joint submission. We simply add, from a CIS perspective, that engineering is but one of many disciplines now being affected by

software. Software engineering is a significant area of faculty growth for both Computer Science and ECE departments across Canada. This creates opportunities for complementary research agenda with lots of potential for synergy. Sufficient mutual understanding and respect exists among software engineering researchers for inter-disciplinary research to succeed.

Senior CIS researchers include Gregor Bochmann, (Ottawa) in formal methods for specification, verification and validation of communications protocols, Ric Holt (Waterloo) in software architecture, patterns and transformations, Robert Probert (Ottawa) in communication protocols, software testing and tools for software engineering, Paul Sorenson (Alberta) in software quality and reuse and Hausi Muller (UVic) in software evolution, reverse engineering and migration of legacy code. Gail Murphy (UBC) is an emerging star in increasing software flexibility. Nancy Day (Waterloo) is a strong junior appointment in formal methods, requirements specification and hardware verification.

Emerging Areas, Interactions and Collaborations

While Canada's traditional CIS research strengths are expected to continue to flourish, it is critical also to emphasize some of the emerging new directions in CIS research, ranging from the theoretical to important new directions of inter-disciplinary activity. Already, a new generation of researchers is moving into these areas. This trend will accelerate.

Bioinformatics and Computational Biology

Computational methods increasingly are important for research in molecular biology and biochemistry. Bioinformatics is a fast-growing and highly inter-disciplinary field that is focussed on computational problems in molecular biology and their algorithmic solution. We expect to see more CIS faculty in this area in the years ahead. In terms of present strength, we mention the Waterloo Bioinformatics Research Group. Janice Glasgow (Queen's) works on molecular imagery. Collaboration in bioinformatics draws from a number of CIS areas, notably algorithms, data structures, AI and databases. Biomolecular computation explores the use of biomolecules and biomolecular techniques to perform computations in a massively parallel way. Specifically, in DNA computing, we mention the work of Anne Condon (UBC) and Lila Kari (UWO).

In the past, biologists have applied ad hoc computational techniques in genomics (the chemistry and structure of genes), proteomics (the structure and function of proteins) and even metabonomics (the biochemistry of metabolic paths). Progress on sequencing the human genome has accelerated research and made bioinformatics a mainstream sub-discipline of information technology. The desire for results has spurred collaboration between molecular biologists and CIS in three key areas: biological modeling; the creation and "curation" of large biological databases; and the development of efficient algorithms to hypothesize and verify the structure and function of biological components at the gene, protein and metabolic levels.

CIS contributes enabling technologies such as computational algorithms for protein sequence matching and database management systems. CIS also contributes more directly, for example, by developing machine learning techniques for large collections of bioinformatic data to test hypotheses explicitly (related, for example, to gene expression evident in microarrays). In future, we anticipate more intimate interaction between computing and biology to model living organisms at increasing levels of specificity and complexity.

Ubiquitous, Pervasive and Tangible Computing
The terms "ubiquitous," "pervasive" and "tangible" computing embody the paradoxical notion that computing will be everywhere while, at the same time, computers themselves will recede into the background. That is, the artifacts humans interact with will contain embedded (and interconnected) computing but the interfaces those artifacts present will be richer and more natural. This area is emerging as a new core of ideas and techniques essential for natural interface devices, interactive workspaces, personal robots, interactive toys and physical simulations in virtual environments, games and animation. Canadian CIS has exceptional potential to lead in this area, with strengths in the constituent sub-areas (HCI, graphics, AI, robotics, distributed and mobile computing and scientific computation) as well as the ability to exploit inter-disciplinary links with psychology (cognitive science) and engineering.

Quantum Computing
Quantum computing has several research foci including algorithms, complexity theory, information theory, physical implementation and cryptography. Two areas aggressively pursued by Canadian CIS researchers are quantum cryptography and quantum complexity theory. So far, quantum cryptography has proven far more accessible to physical realization than have quantum Computing and algorithms. Quantum cryptography now spans the gamut from prototype implementations of secure transmission to fundamental theoretical studies. Quantum information theory evolved from research in quantum cryptography. Fundamental unifying ideas are appearing that will have important consequences for theory and perhaps for practice.

Physical realization of quantum algorithms remains distant. But, the subject provides deep insight into quantum complexity. The view that quantum decoherence is the bane of algorithms led to new results in quantum error correction. We expect major progress in quantum complexity, especially in quantum communication complexity.

Interaction with physics is of mutual benefit. Results on quantum teleportation arguably could have been discovered in the 1920s. But, it was research in quantum computation that led to their discovery. In the area of quantum computing, Canadian CIS researchers will continue to play a leading role in these and other multi-disciplinary discoveries.

Information Management
Coping with information overload is an important challenge. According to one estimate, the world produces 1-2 exabytes of data per year, that is roughly 250 megabytes for each man, woman and child on the planet. Only .003% of this data is produced in print form.

The rest is either produced in digital form, or in forms that are rapidly becoming digital, such as video and film. Data increasingly is shared and shipped around the world, causing Internet traffic to double every year. Many sub-disciplines will need to collaborate to discover the new principles and to develop the new tools to cope with this deluge of bits. Information retrieval and database management, two almost disjoint areas in the past, are already collaborating to improve Web searching and to deal with structured, unstructured and semi-structured data such as XML. Data mining and knowledge discovery will work to automate the process of extracting significant patterns from masses of data, in collaboration with machine learning and statistics. Computational linguistics and knowledge representation will work to extract meaning from data and to encode meaning in it. Processing of multimedia and other streaming data increases in importance as image, sound and video become part of our digital universe. New sources of data are important too, including data from the Web itself and from biology. The trend is towards accessing information from anywhere and at any time. Problems in mobile computing will be addressed in several areas including HCI, networks and operating systems.

Health Informatics

Health informatics deals with the use of computing and information technology in health research, education, patient care, policy setting and health services administration. Each Canadian provincial government administers a single-payer public health care system that collects and maintains comprehensive data on all aspects of medical care. Comprehensive data from a single source provides unique opportunities for health informatics research. There have been health informatics graduate programs and research centres in the US and Europe for some years. But it is a relatively new area in Canada. Recently, there have been collaborative efforts among several universities across Canada to develop new graduate programs and research in health informatics. This has led to new collaborations between CIS and researchers in the health field. Canada has both the social will and the opportunity to lead in all aspects of health care. We expect that CIS researchers in a wide range of areas will find health informatics both a useful source of research problems and an appropriate target for the application of research results.

Nanotechnology

Molecular machines are revolutionary. The scope of application is as wide as things made of atoms and molecules (i.e., everything). Current examples are experimental. Nevertheless, nanotechnology has become part of the research agenda of key government agencies.

CIS has a leadership role to play. Physical science is central to understand molecular level interaction at the nanometer scale. CIS contributes enabling technology for basic scientific investigation. More critically, CIS contributes operational models for both sensing and manipulating matter at the molecular level. The atomic resolution microscope (ARM) is one example. Another is the construction of devices and structures from DNA and the manipulation of synthetic DNA on silicon chips. Computational models are needed to design molecules with the desired structure and function. Many more examples will emerge. Useful molecular level machines will require computational models for their construction and use.

Electrical and Computer Engineering

Research Excellence

Canada has been in the forefront of Electrical and Computer Engineering development and innovation for over 100 years. Some historical highlights of significant Canadian ECE milestones are given below:

1876: Alexander Graham Bell has spoken the words "Mr Watson, come here, I want you," and the telephone was born;

1901: Guglielmo Marconi, in St. John's, Newfoundland, receives transmission from Land's End in Cornwall, England, 2,170 miles away. Marconi sets up permanent base at Glace Bay, NS. What is now Canadian Marconi was founded in 1902.

1951: In Electronic medicine, a Canadian team developed the Cobalt Bomb, prolonging the lives of thousands of cancer sufferers. Also in the same year, Dr John Hopps of the National Research Council builds the world's first heart pacemaker.

1962: *Alouette I*, Canada's first satellite is launched and Canada becomes the third country (after the US and USSR) to have a satellite in orbit.

1969: Telesat Canada is formed and *Anik I* becomes the western world's first communications satellite. Canada establishes the world's first domestic communications satellite system.

1976: Northern Telecom (now NORTEL Networks) announces the Digital World and becomes the first corporation in the world to commit to the introduction of a complete family of fully digital switching and transmission systems.

1981: The Canadarm, a 15-meter electronic remote manipulator system, comes to life aboard the *Columbia* space shuttle. Telidon, a videotext system, an entirely new technology developed by the federal Dept. of Communications, was tested in Manitoba. The technology was far superior to the French Minitel but its marketing was not successful.

The Canadian Electrical and Computer Engineering Departments and their graduates have been responsible for many of the above innovations. The quality of the ECE undergraduate programs is not only established by their periodic accreditation by the Canadian Engineering Accreditation Board, but more importantly by international comparisons, especially with much bigger and wealthier US Universities. Using a sophisticated set of proprietary indicators, an American rating company periodically produces the Gourman Report – a document in which US and Canadian University programs are ranked on a scale from 1 (low) to 5 (high). In the most recent available survey [Gourman], the University of Toronto Electrical Engineering program was rated 4th (with a score of 4.86), just after MIT, Stanford and UC Berkeley. Three others were in the top 10, while 23 overall Canadian Electrical Engineering programs were ranked in the top 50 North American programs, with scores better than 4.44.

These excellent Canadian undergraduate programs have provided very high-caliber graduate students and researchers to our universities, and also very capable engineers to our industry. The international competitiveness of leading Canadian companies such as Nortel Networks, JDS Uniphase, Mitel, Gennum, Newbridge/Alcatel Canada, IBM Canada and dozens of others is due to the quality of their Electrical and Computer Engineers.

Research support to Canadian ECE researchers is mainly coming from NSERC programs and Centres of Excellence (provincial and federal), and to some extent from industry and government grants and contracts.

NSERC individual operating grants are the backbone of Canadian ECE research. Having those, generally small, grants constitutes a honor that few Canadian academics can do without. They also permit program (rather than project-oriented) research, which offers tremendous advantages for innovation. In addition, NSERC strategic and university-industry grants, which are more project-oriented, bring significant research funding and enhance interaction with industry and the creation of intellectual property. With the support of NSERC, our ECE departments have built very high-quality programs. In addition to providing our above cited high-technology industry with highly qualified manpower, they have also transferred technology to industry and helped set up and run small and medium-size enterprises.

With strong support from industry and government research laboratories, ECE researchers were very successful in the competitions for federal Networks of Centres of Excellence (NCE), which were meant to stimulate research excellence and enhance industrial innovation and competitiveness. Since 1990, NCEs such as the *Canadian Institute for Telecommunications Research (CITR*), the *Microelectronics Research Network (MICRONET)*, the *Institute for Robotics and Intelligent Systems (IRIS)* , *Intelligent Sensing for Innovative Structures (ISIS)*, the *Canadian Institute for Photonics Innovations (CIPI),Mathe matics of Information Technology and Complex Systems (MITACS), The Automobile of the 21st Century (AUTO21)* and the *TeleLearning Network of Centres of Excellence (TeleLearning-NCE)* were established with many ECE researchers as their principal participants. Eight of the 22 (36%) established NCEs have ECE principal investigators. This further testifies to the research excellence of the Canadian ECE community.

Seven Ontario Centres of Excellence were founded in 1987. They were consolidated in 1997 into four: *Communications and Information Technology Ontario (CITO)*, the *Centre for Research in Earth and Space Technology (CRESTech),Mate rials and Manufacturing Ontario (MMO)*, and *Photonics Research Ontario (PRO)*. ECE researchers are involved in all four, but principally in CITO and PRO. Industry participation in all centers has been a government requirement and has benefited the Ontario university system enormously.

The Government of Alberta established the *Alberta Telecommunications Research Centre (ATRC)* as a joint industry-university telecommunications research enterprise in

1987. Gradually expanding beyond provincial boundaries, by 1992, the ATRC had became the *Telecommunications Research Laboratories* – TR*Labs* for short. Providing ECE researchers in Western Canada with a solid interface into the leading telecommunications companies in North America, the TR*Labs* consortium now represents a research network comprised of many industrial members, universities, four governments, nineteen small business associates and eight strategic alliance partners. In 1999, the Government of Alberta identified ICT as an area of substantial funding by forming iCORE, a centre of informatics identifying and funding research in the most promising areas of communications, nanotechnology and high-performance computing. Another successful model to foster research excellence and university-industry co-operation is the *BC Advanced Systems Institute* set up by the Government of British Columbia.

The Canada Foundation for Innovation (CFI) is an independent corporation established by the Government of Canada in 1997. The CFI is responsible for a budget of $3.15 billion. These funds are invested in partnership with the institutions and their funding partners from the public, private and voluntary sectors. By funding research infrastructure projects, the CFI supports research excellence, and helps strengthen research training at institutions across Canada. On average, the CFI contributes 40% of total eligible project costs. Based on this formula, the total capital investment by the CFI, the institutions and their partners will exceed $7.0 billion by 2010. Canadian ECE research has obtained world-class facilities, thanks to major CFI funded projects.

In its 2000 budget, the Canadian federal provided $900 million to support the establishment of 2,000 Canada Research Chairs in universities across the country by 2005. The key objective of the Canada Research Chairs Program is to enable Canadian universities to achieve the highest levels of research excellence and to become world-class research centres in the global, knowledge-based economy. Many distinguished ECE researchers have been appointed to Canada Research Chairs.

These initiatives attest to the high level of research excellence and industrial collaboration achieved by ECE researchers during the past dozen years. They stimulated the recruitment of talented researchers to many universities, taught young faculty that research excellence and economic value are compatible objectives, and provided countless examples of successful technology transfer. Moreover, research quality improved very substantially as the various centres used panels of international experts and highly qualified industrial practitioners to evaluate and critique research proposals. In effect, our community has, does and will continue to play a vital role in building and maintaining globally competitive, knowledge-based industry.

There are many senior and distinguished Canadian ECE researchers who hold Canada Research Chairs, are Fellows of the Royal Society of Canada, of the Canadian Academy of Engineering, of the IEEE and several other prestigious organizations. We will not highlight their excellence in this report. Instead, we want to bring forward some of names of our young rising stars and some senior researchers attracted to Canada from abroad.

Dr. Lawrence R. Chen is a new Assistant Professor at McGill University (Ph.D., Toronto, 2000). His research was highlighted by NSERC Grant Selection Committee 334. His current research interests focus on enabling technologies for high-performance lightwave transmission and include fiber amplifiers and lasers; fiber gratings; spectrally efficient modulation formats; and optical code-division multiple-access. Dr. Chen is a rising Canadian star in optical engineering.

Dr. Andreas Moshovos is an Assistant Professor at the University of Toronto (Ph.D., Wisconsin, 1998). He is also highlighted by the NSERC GSC 334 for developing techniques to "empower" future micro-processors. He is working on Clustered Architectures and Slice Processors, Self-Micro-Reconfigurable Processors and Software/Hardware Techniques for Reducing Power. He is one of the brightest rising stars in Computer Engineering.

Dr. Cyrus Shafai is an Assistant Professor at the University of Manitoba (Ph.D., Alberta, 1998). He received his Ph.D. for the development of a micromachined Peltier heat pump, which can be used for on-chip temperature control, and as a micro-calorimeter for reactants of 10's - 100's of picolitres. He also pioneered the development of the Scanning Resistance Microscope, which can delineate regions of different semiconductor doping with 20 nm resolution. He is currently applying micromachining to next generation millimetre wave RF systems. He is one of the bright rising stars in Electrical Engineering. There were two senior new applicants in the 2001 NSERC GSC 334 grants competition with excellent international reputations, who have moved to Canada. They are **Dr. J. S. Aitchison** (Toronto) and **Dr. J. B. Kuo** (Waterloo). Both are significant additions to the Canadian research community.

Dr. J. Stewart Aitchison (PhD, Heriot-Watt University, UK). He is now a *Professor and Nortel Institute Chair in Emerging Technology* at the Edward S. Rogers Sr. Dept. of Electrical and Computer Engineering at the University of Toronto. His work deals with All-optical switching and signal processing, Optical frequency conversion and parametric interactions, Novel optoelectronic materials and photonic microstructures for linear and nonlinear applications, Optoelectronic integration and bio-sensors for lab-on-a-chip applications.

Dr. James B. Kuo, FIEEE, (PhD, Stanford University). He is now *Professor and Canada Research Chair in Low Voltage CMOS* at the University of Waterloo. He is well-known for his work on "silicon on insulator" device technology. His research expertise is in the field of low-voltage CMOS VLSI circuits and SPICE compact modeling of deep-submicron bulk and SOI CMOS and BiCMOS VLSI devices.

These are just samples of the outstanding researchers that the NSERC Research Grants program has supported in the 2001 grants competition. When coupled with high quality research supported by the various Centres of Excellence and industry, Canadian research in ECE is at the cutting edge of developments in many areas and is significantly impacting technology evolution worldwide.

A Vision for the ECE Discipline in Canada

The research fields in ECE are rapidly evolving. Based on past accomplishments and research excellence, outlined in the previous sections, the Electrical and Computer Engineering Discipline in Canada is focusing its Vision for the next 20 years on: *"Making Canadian research and researchers in Electrical and Computer Engineering a force of national pride, internationally acclaimed, and a driver for competitiveness and progress in a World context, where Information Access is Instantaneous, Always Available Everywhere, Portable, Personalized, Reliable and Secure, and contributes to enhanced Health Care and Economic and Social Prosperity."*

In addition to such established ECE areas as Power, Control and Systems Engineering, which continue being of great value to society's infrastructure and the backbone of ECE research, future Canadian ECE research will focus on the following emerging areas of Canadian and international importance:

- *High-Speed Micro- and Nano- electronics*
- *Photonics engineering*
- *Personal and Wireless Communications, including new smart antennas technologies*
- *Nanotechnology in Biomedical engineering and Biometrics*
- *Ubiquitous Computing and new Computer Architectures*
- *Internet Technologies and Networks*

With increased NSERC funding, and Centres of Excellence and CFI Infrastructure support, ECE researchers in Canada will continue being internationally competitive in the above areas. A brief description of research trends in these fields is given below.

Future Trends in Micro- and Nanoelectronics

Microelectronics and nanoelectronics are the enabling technologies which have made and will continue to make developments of the information-communication sector possible. ECE research challenges in this area are many.

At the device and technology levels, the challenges include devising: techniques to scale device dimensions down to the 100nm level and below, nanoelectronic devices (based on novel materials such as carbon nanotubes) and generated by chemical self assembly techniques, which circumvent the necessity for conventional lithography, methods of integrating advanced capabilities into conventional processes such as the development of high power devices, micro electromechanical structures (MEMs) and microphotonic (combination of microelectronics and photonics on the same chip) structures to circumvent the limitations of conventional methodologies in the implementation of future electronic systems on a chip (SOC), interconnect techniques necessary to implement very large-scale circuits on a chip, and CAD tools, models and metrology necessary to design and characterize nanoelectronic structures.

At the circuit and system levels, challenges include developing: design environments for system on a chip implementations, mixed analog-digital circuits design methodologies for high-speed, low-voltage implementations needed to reduce power dissipation in communications and multimedia digital signal processing applications, broadband wireless and wireline communication interfaces to carry voice, data and video and to implement the "last mile" interconnection between the information provider and the users, electronic interfaces for fiber optic communication systems, techniques for multicomponent microsystem integration, novel design methodologies using artificial neural networks, cellular automata and quantum computing to optimize the implementation of electronic systems, methods for fast turnaround system design, and test strategies for the verification of complex circuits and systems.

New Directions in Photonics Engineering

Photonics' range of applications extends from energy generation and detection to communications technology and medicine. The tremendous recent interest in photonics relates especially to its use in the telecommunications sector, where fibre optic waveguides are used to convey streams of digitized information over large distances and at high data rates. The field of photonics clearly has major potential for future development, across a wide range of applications. Optically based elements used as a platform for computing will enable a new expansion in data processing capability.

Optical memory and switching elements will enable data storage (with high-speed write and retrieve capability) and the direct switching of optical signals without having to revert to the electronic domain. In the same way that compact discs brought high-quality stereophonic audio to domestic users of all ages, we can anticipate future advances in optics to provide convincing three-dimensional holographic full-colour imaging. The technology has many other applications, in health, education, military, security and other sectors, but the recreational market will help to bring costs down to the levels of ubiquitous access.

In health care, hospitals are using tele-monitoring services to ease the in-patient or out-patient load of post-surgery follow-up, and to monitor personal health data (blood-sugar levels, heart-rate, blood pressure, urinalysis, etc). The scope for effective coverage of patient monitoring needs, particularly in our aging population, will develop markets for the optically based devices needed in these applications. As we enter the post-genomic age, there exists the ability to, in a massively parallel approach, ascertain the genetic make-up and genetic activity of any accessible tissue in any given individual. While this application, which is currently taking medical science by storm, is implemented utilizing DNA microarrays or chips, there is a general consensus that a fibre-optic approach will be the way of the future. Whereas DNA microarrays are prepared as planar chips, a novel and promising approach will involve converting individual optical fibres into DNA or protein sensors. Emerging technologies involving ultra-fast femtosecond pulsed laser sources, non-linear optical components allowing visible wavelength optical parametric generation schemes, improved highly sensitive light detectors, novel fluorescent probes coupled with high-speed low-cost digital signal processor technology are rapidly paving the way for quantum leaps in instrument design for optical microscopy and microspectroscopy in cell biology, genetics, biochemistry and protein chemistry. The rapid technological innovation in the field of photonics will revolutionize all of the applications mentioned.

Future Directions of Nanotechnology in Biomedical Engineering and Biometrics
New medical breakthroughs in cellular drug delivery, spinal cord repair, organ growth, are brought to us by biomedical engineers working in the developing field of nanotechnology. Engineers are working on extremely small machines and tools that can enter the human body, perform diagnostics and potentially repairs. For example, nanoshells have demonstrated the potential to provide instantaneous blood-test results and eliminate long waiting times [Kowalenko]. Nanobiosensors can be created to reliably detect pathogens such as viruses. "Biology is becoming a substrate of Engineering" [Institute]. Other areas which will be affected by nanotechnology include biometrics, telemedicine, and diagnostics. Biometrics deals with sensors, bioscans, imaging, and identification. Telemedicine includes medical data acquisition, compression, transmission, display, etc. Diagnostics include biological signal acquisition, modeling, decomposition, interpretation and classification.

Future Trends in Wireless Communications
The telecommunication industry has experienced a revolution over the last decade due to wireless communication technology. Its future growth will be mainly based on the integration of the Internet with wireless communications in the form of highly intelligent multimedia terminals endowed with computing power and advanced networking facilities to serve business and mobile personal users. The extraordinary and explosive growth in mobile and wireless communications will continue to stimulate advances in a variety of fields and to push the development of new technologies for further improving the system capacity, performance and cost. In particular, various challenging issues must be addressed such as: higher speed transmission technologies (including advanced coding and modulation), multimedia transmission for wireless systems (new signal processing technologies), wireless mobile Internet (radio resource and mobility management, wireless Internet access, mobile-IP, authentication, security, mobile commerce over wireless networks, adaptive quality of service support for multimedia wireless networks, and ad-hoc wireless networks), software radio(including architectures that optimize software and re-configurable hardware), low power Radio Frequency systems (micro-mechanical systems on chips, optimization of RF front-ends), Radio Frequency Integrated Circuits and Antennas (use of RF CMOS, Bipolar or SiGe Bipolar to reduce cost and allow more functions to be integrated, "Smart Radios" allowing the performance of the entire system be controlled, adjusted or calibrated by digital functions, efficient and extremely fast signal processing algorithms for smart antenna realizations, substrate design using micromachining and microfabrication). Canadian companies have indeed made significant impacts and numerous innovations in this field with obvious socio-economic benefits for Canada. The worldwide forecasts for the growth of mobile and wireless communications are very optimistic and this growth is expected to be very strong in the years to come. As a result, Canada's involvement in further developing rapidly evolving wireless technologies is necessary and valuable, if Canada is to achieve its long term industrial and economic goals.

New Directions in Computer Engineering

The rise of Internet technologies and standards in recent years has caused a very rapid convergence of computing and communications technologies. So far, four major periods can be distinguished in the development of the computing industry. The first era was that of central mainframe computers, spanning the years 1950 to 1980. The second was the PC era which began in the 1980s. The third was the network era, which started in the 1990s with the rapid growth of the Internet and computer networking. This era is generating dramatic changes in the nature of work and commerce and in the structure of the industry. While it is still unfolding, a fourth era is emerging. This will be the era of *Pervasive (or Ubiquitous) Computing* where the emphasis shifts from information and communication technologies to information and communication per se. Computers will become a pervasive technology, that is, a technology more noticeable by its absence than its presence. Already in 2000, from the 8.3 billion CPUs produced in that year, 80% were used in embedded computer systems, 6% in robots, 12% in automotive systems and only 2% in conventional computers! Pervasive computing will give us tools to manage information easily. We expect devices – personal digital assistants, mobile phones, NetTVs, office PCs and home entertainment systems – to access information and work together in one seamless, integrated system. This is opening up a vast new area for ECE research. How will a myriad of heterogeneous intelligent information appliances be interconnected, using new wireless and wireline networking architectures? How will they communicate with each other, possibly using intelligent agents and new management structures? How will they be part of the intelligent city of the future? How will new databases address the need of this new technology and how will the human-to-device interface be made using voice recognition, voice synthesis, retinal movements, muscle control and other methods?

With hundreds of millions of computers worldwide, and with this number soon to grow into the trillions, the number of components on a computer chip continues growing annually by a factor 1.5 - 2 (Moore's Law). Assuming that the exponential growth law will not be impeded by external factors (like the general state of the world economy), current chip technology is expected to find its limits around the year 2010. Transistors will have become so small by then that their mass production will be very difficult and expensive. Moreover, the operation of "nanotransistors" will be governed by quantum phenomena rather than classical electronics. Thus, further miniaturization will require a completely new technology which is largely *terra incognita* today. It should also be realized that even "straightforward" stepwise extension of today's technology is a multi-billion dollar affair. It is sometimes stated, based on the extrapolation of Moore's Law, that around 2020 a chip will have 100 billion (10^11) components, (i.e., the number of neurons in the human brain). There is a vast gap, however, between our capabilities to built complex hardware and our insight in how to exploit this complexity. Addressing this gap will open up many fascinating areas of research and applications. For example, the use of nanostructures in computing and the use of parallel and quantum distributed computing need to be investigated. New *application domains* will include virtual reality, multimedia technology, medical image processing, intelligent autonomous systems (robots) for industrial use and large-scale simulation.

Future Trends in Internet Technologies and Networking

The Internet has evolved from one host computer at UCLA in 1969 to 120 million hosts, covering the world and connecting 435 million users in Aug. 2001 (statistics from the *Telcordia Netsizer*). It is now growing by 40-50% per year and it is projected that 700 million people will be using it by 2005. The Internet has been functioning without major outages, due to its highly adaptive routing algorithms. The TCP/IP protocol stack became the heart of the Internet and eventually a de facto world standard, eclipsing international standards for transport and network layers. This protocol, however, designed for file transfers over a noisy network infrastructure of the early 1980's, does not allow the current Internet to provide adequate Quality of Service (QoS) for new multimedia services that demand fast response, high bandwidth and low losses. New procedures, such as the *Reservation Protocol* (RSVP), *Integrated Services, Differentiated Services and Multi-Protocol Level Switching* (MPLS) will allow Internet routers to provide various degrees of QoS in the near future. Further QoS enhancements will be provided by the next generation IP protocol (IPv6), which is to be widely deployed over the wireless Internet, with a trillion of interconnected sensors, appliances, other pervasive competing devices and users. Internet QoS has been a very intensive research field in Electrical and Computer Engineering and will continue being so in the future. Network processors will play a major role in the new Internet, where the data rates will move 40 Gb/s (OC-768) within the next few years. In the past, there was not much need for dedicated network processors, as general-purpose processors were able to keep up with the data flow. In the future, Network processors will be optimized to process data packets and send them fast to the next node in the path to the destination. They will soon reside in every piece of networking or communications equipment, e.g., routers, switches, servers, gateways. *New architectures for network processors* will have to be developed. The wireless will need new wireless network architectures for interconnecting pervasive computing appliances and sensors. New QoS procedures will have to be found, since wireless will remain prone to transmission interference and errors. *New Radio Frequency bridges to the network will be needed. Network simulation and testing tools* will remain very valuable and implementation of their design will be intense. In the domain of *multimedia Internet applications*, streaming video and audio will continue to impose stringent requirements for Quality of Service and new solutions will have to be developed. New coding schemes for audio and video will lead to new standards in that area, beyond the current MPEG and JPEG families. Digital Watermarking for images, video, audio and graphics will continue being a hot area for research, as copyright and protection issues for digital content are key ingredients for e-commerce. Furthermore, Distributed Virtual Environments are emerging as a new "medium" for Web-based education/training, military simulations, e-commerce, entertainment and other applications. Research in this area will intensify, as Virtual Reality has now come to the desktop computer. Next generation web protocols research, including secure protocols, will be very active as the WWW is the most rapidly growing Internet service with vast area of applications. *Information security, including encryption, resilience to intrusion and other attacks*, are also most promising areas for ECE research.

Interdisciplinary Materials Research

Strategy

Canadian chemists and physicists have an established record of excellence in collaborative materials research. Collaborations have led to both novel materials and concepts, benefiting both communities and pushing the limits of their skills and capabilities. Outstanding examples of joint projects include: the synthesis and understanding of the properties of organic materials, superconductors, self-assembled structures, complex magnetic materials, and photonic crystals. The two disciplines are now simultaneously converging on the area of nanoscience and will lead the country in this growing field. An outstanding example of chemistry-physics collaboration, highlighting Canadian work on magnetic materials, is given in the cover article of *Science* of November 16, 2001.

Existing collaboration between chemists and physicists in Canada is also evident by interdisciplinary scientific associations such as the Canadian Institute for Synchrotron Radiation, which coordinates the activity of 500 Canadian synchrotron users, and the Canadian Institute for Neutron Scattering which has over 250 Canadian members. In addition, the Canadian Association of Physicists and the Canadian Society for Chemistry jointly sponsor a Surface Science Division. There are also large collaborative research efforts involving chemists and physicists such as the superconductivity and nanoelectronics programs of the Canadian Institute for Advanced Research, as well as the Canadian Institute for Photonic Innovations, one of the programs of the national Network of Centres of Excellence.

However, the above programs support targeted research with defined applied goals. We believe that collaborative and basic materials research at the level of two or three researchers funded via the NSERC Research Grants is also indispensable. Collaborative projects are frequently highly exploratory and thus risky but they often lead to the most novel outcomes, including those that generate entirely new fields. The potential for completely unexpected outcomes, the impact on other disciplines, and the broadened scope of the fields involved, justify the increased funding that might be necessary to carry out such collaboration. The strategy is to supplement Research Grant funding at modest levels ($5,000 to $20,000 per annum) meeting needs distinct from those supported by other programs, such as the NSERC Collaborative Research Opportunity Grants (CROG) Program. The CROG program, for example, supports major interdisciplinary or international projects with specific problem-based goals requiring at least $100,000 per annum. Our strategy will be to provide funds sufficient to encourage collaborations between chemists and physicists, enhancing opportunities for new science and interdisciplinary training in Canada.

There are many exciting new fields where future interdisciplinary collaborations between chemists and physicists in Canada are likely. The areas highlighted below are meant only to be illustrative, not to limit the scope of possibilities. However, each has significant socioeconomic impact and is already receiving priority investment in Europe, the US and Japan.

i. Nanoscience: As the size of materials and structures (crystals, membranes, fluids) approach nanometer dimensions, their properties diverge remarkably from the bulk values. At the nanoscale, our conventional understanding of mechanical, electronic and optical properties breaks down, opening fascinating new opportunities for discoveries and applications. We are on the threshold of an era of nanofabrication for a broad range of electronic, magnetic and photonic devices and systems. Nanoscale structures have significant implications for increased computing power, microlasers, innovative new sensors, biochips and photonic bandgap circuits for processing information. Viable approaches for reliable and uniform nanoscale materials preparation, suitable for preparing large numbers of features within tightly controlled dimensional tolerances are urgently required. The field is a gold mine of opportunities for joint research between different disciplines, but especially between chemists and physicists. Their combined perspectives and capabilities will dominate the fundamental advancement of this field.

ii. Microfluidics: Microfluidics involves the study and application of fluid flows in micron scale structures. The research involves both chemistry and physics for the development of new fabrication methods, the invention of components to control, transport, mix and separate fluids and the study of the fundamental behaviour of fluids on micron length scales. Applications of this research include the development of new sensors for biological, medical and environmental applications. Indeed, so-called "lab-on-a-chip" systems, based on microfluidics, are marketed by Micralyne, a Canadian company in Edmonton.

iii. Synchrotron Science: A major Canadian initiative, involving a significant fraction of the physics and chemistry community, is the design and construction of the Canadian Light Source, a 2.9 GeV third-generation synchrotron, to be available in 2004. This facility will support a wide range of cutting-edge research and industrial applications from the hard X-ray region to the far-infrared. It will provide superb teamwork training opportunities for students on forefront materials projects, such as probing novel photonic properties of nanomaterials and compound semiconductors, spectromicroscopy of thin films, polymers, protein crystals and biological tissues, and far-infrared spectroscopy of important environmental and astrophysical molecules.

iv. Neutron Scattering Research: Neutron scattering is an essential tool for many aspects of materials research. Canadian contributions involving the use of neutron beams for research in materials science and engineering are among the most significant worldwide, starting from Brockhouse's pioneering studies in inelastic neutron scattering, for which he was awarded the 1994 Nobel Prize in Physics. The Canadian neutron scattering community in 2001 is large and interdisciplinary. In addition to travel to the Chalk River facilities, Canadian chemists and physicists travel to perform neutron scattering research at international "cold source" facilities. There are many opportunities for collaboration with this community.

v. New Analytical Tools: Many materials advances involve the development and/or application of new analytical tools by one collaborator, applied to materials synthesized by the other. Current Canadian examples include: the development of optically pumped THz spectroscopy to perform non-contact characterization of the transient photoconductivity and carrier dynamics in materials; the study of atomic processes during reactions; and a Canadian-American collaboration leading to the first scanning transmission X-ray microscopy. The rate of development of new techniques in Canada is high and it is driving new understanding of materials.

vi. Laser Machining: The rapid emergence of robust femtosecond laser systems presents opportunities to micromachine precisely virtually any material, to modify optical materials through nonlinear interactions and to write three-dimensional structures inside optical materials. The high laser intensity produces nonlinear multiphoton phenomena that modify bond structures below damage threshold intensities and change crystal structures and refractive indices. These advances can be applied in a number of areas including high-intensity multiphoton writing of waveguides in glasses and nonlinear optical materials, and the ablative micromachining of submicron structures such microelectromechanical systems (MEMS).

vii. Plasma Applications: Plasmas are at the heart of numerous industrially important technologies including microelectronics, telecommunications and photonics. Their contribution to these sectors and basic research is growing rapidly. The nature of plasma research and its applications requires the development of a multidisciplinary approach that combines theoretical and experimental knowledge of various sources such as plasma discharges and laser plasmas, together with expertise in the domain of the application (e.g., materials science). Plasmas are involved in the synthesis of novel materials with specific properties, including nanostructured materials (nanotubes, nanoparticles), the modification of materials (e.g., for implantation), and their analysis (e.g., laser-induced plasma spectroscopy). Several Canadian teams are strongly involved in the development, characterization and applications of plasma sources for materials.

viii. Synthesis and Characterization: The predominant class of joint chemistry-physics materials research projects is the synthesis and characterization of novel materials and structures. These include novel superconductors, organic materials, liquid crystals, conducting polymers, photonic crystals, self-assembled films, nanomaterials, holographic materials, etc. Undoubtedly, future collaborations in this field will be driven by the synthesis of new materials, a very active area of research in Canada, by both conventional and combinatorial methods.

Chemical and Metallurgical Engineering

Strategy

Our strategy derives directly from our vision for the discipline in Canada and the role of GSC 04 in achieving the vision. It relies on the demonstrated achievements and excellent record of GSC 04 researchers in producing world-class leading research, with relevance and important benefit to Canada. It recognizes that GSC 04 researchers will continue and expand their collaboration with Canadian industry, thus substantially leveraging the NSERC Individual Research Grants. Furthermore, they will intensify their successful efforts in training of qualified human resources, developing new technologies, and creating spin-off enterprises.

Application of New Technologies in Canadian Resource Industries. For Canada to sustain its standard and quality of life in the 21st century, both the traditional and new technology sectors of our industrial economy must succeed. The resource and manufacturing industries, the economic backbone of the country's prosperity and quality of life, face the challenges of rapid advances in information, control, and process technologies and new value-added product development. The petroleum, oil and gas processing, mineral and metal processing, chemicals and petrochemicals, food processing, forestry and agricultural industries must continually develop and adopt leading edge technology in their production processes to remain globally competitive as well as environmentally responsible and sustainable. They must upgrade their output from raw materials or bulk low value products to new higher value products, to ensure their viability and retain in Canada greater economic value, be they, for example, specialty chemicals, lightweight steels and steel alloys or enzymes from agricultural products. Committee GSC 04 will encourage research that contributes to the strengthening and sustainability of the Canadian resource industries by application of advanced and emerging technologies and by training highly qualified personnel in relevant fields. For example, we need to intensify current leading research to develop clean/green fossil fuel based on Canadian resources. Also, there are great opportunities and efforts underway in Canadian universities to exploit the full mechanical property potential (e.g., modulus, toughness, and strength) of materials such as steel, aluminum and magnesium. The potential for these properties is about an order of magnitude higher than existing values. Similar potential exists for upgrading the properties of commodity and high performance polymers, through structure manipulation and process control.

Research in Sustainable Emerging Technologies. In Canada's emerging new high technology economy, a rapidly expanding number of small but growing companies, operating in a wide array of areas of advanced technology, face the challenge of building a sustainable future in the highly dynamic and competitive economy of the 21st century. These companies cover a broad range of emerging fields, such as biomaterials and biomimetics, gradient and functional materials, pharmaceuticals, electronics and optoelectronics, fuel cells, polymers, composites, specialty metals and alloys, advanced coatings, nanotechnology, specialty agricultural and food products, etc. They rely on leading-edge information technology, modeling and simulation, new processes, combinatorial high throughput evaluation and development, sensors and control, chemical and materials science and engineering, etc. as their "raison d'être" or core competitive advantage. GSC 04 will encourage research and the training of highly qualified personnel to help the establishment, growth, strengthening and sustainability of emerging technologies in Canada.

Research Clusters and Interdisciplinary Collaborations. New and established researchers in GSC 04 have the skills, abilities, potential and flexibility to participate in multi-disciplinary research, that is required to upgrade and strengthen resource-based industries and to make innovative contributions to the emerging new technologies. After careful consideration, the Steering Committee concluded that it is not possible or advisable to attempt to achieve our objective within the framework of but one or two new interdisciplinary committees, in view of the nature, interests and activities of our researchers and the needs of our research. However, our strategy recognizes the need for and importance of collaborative interdisciplinary research and will employ a strategy that encourages GSC 04 researchers to pursue practical and fruitful interdisciplinary collaborations in directions that are relevant to Canada. Similarly, GSC 04 will encourage researchers to form and become part of research clusters that will help them to maximize the human and physical resources and capabilities needed for process and product research and innovations. Collaborations and clusters will be encouraged locally, nationally, and internationally, involving academic, industrial and government researchers.

CFI-Funded Projects. Many of the established and young researchers have received or participated in successful major infrastructure grants from the Canada Foundation for Innovation and other agencies. These grants provide opportunities for enhanced research quality and training of graduate students and post-doctoral researchers. The infrastructure, instrumentation and equipment resources made available by these grants will require significant maintenance and additional human resources to ensure their proper and optimum operation and use.

Appendix D[64]
PRECARN/IRIS Report on Canadian Research Capability in Autonomous Robotics Survey

Further to our meeting, Rick Schwartzburg (IRIS contacts) and Celeste Burnie (PRECARN contacts) contacted our mailing lists related to robotics and automation research. We asked three types of questions:

1. Are you working in this area? Do you know someone who is? Can you identify other sources of info?
2. What are the major technological challenges?
3. What are some potential applications?

We surveyed about 75 academics and about 67 PRECARN contacts. We had responses from 13 academics and 5 companies.

1. PEOPLE WORKING IN THE AREA

There are significant pockets of academic expertise in Canada in the mobile robotics area. Mostly these are with wheeled ground vehicles, although there is also work on underwater vehicles and walking robots (even one walking, underwater robot). There is little work on "swarms" although a number are working on issues related to large groups of robots. I have not seen any evidence of work on "micro" or smaller robots.

The McGill Centre for Intelligent Machines and in particular, Dr. Greg Dudek, seems to be a leading "centre of excellence" in this area. Not only did Dr. Dudek respond, a number of other respondents referred to him as a leading player in Canada. He has been working on mobile robots for over ten years; groups of robots for seven; and, large groups for about the last two or three years.

There is also expertise at the University of British Columbia (especially in the "intelligence" and "sensing" areas). We also have people at University of Calgary working on issues like: resolving conflicts between robot sensors (are they sensing the same thing? is one sensor broken? is there "noise" in the system?, etc.) Other people working with American companies on fleets of small UAVs (the person didn't want me to reveal their name or the company they are dealing with at this time; however, they would discuss this with you at an appropriate time). Of course, we have UBC, Simon Fraser University and McGill which has groups that participate in the world robot soccer competitions, which train students in all the relevant technologies.

Companies working in this area are:
1. MD Robotics, Toronto
2. Inuktun, Nanaimo
3. ISE, Port Coquitlam
4. Intrignia, St. John's

2. MAJOR TECHNOLOGICAL CHALLENGES

A significantly large majority of the respondents identified the two most difficult challenges facing progress in large groups of autonomous robots:

1. Collective intelligence
    a. coordinated data acquisition,
    b. collective decision making,
    c. shared knowledge,
    d. distributed processing, etc.),
2. Distributed perception.

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[64] Written by PRECARN in support of this effort.

3. Distributed control, and,
4. Communications, especially in a "dirty" or "noisy" environments.

Surprisingly, a number said that "locomotion" was not an issue; however, it is believed that they were saying this in relation to small but NOT microscopic or (certainly) nanoscopic-sized robots.

3. POTENTIAL INDUSTRIAL APPLICATIONS

A number mentioned military applications; I will just list the other industrial thoughts:

1. Firefighting
2. Exploration, surveying, mapping
3. Self-adjusting, self-organizing highly-versatile assembly lines
4. Mining
5. Search and rescue
6. Planetary exploration
7. Surveillance and security
8. Entertainment (game playing robots)
9. Pollution clean-up
10. Agricultural harvesting

Appendix E
DARPA Project Funding Model

for:

"Highly Imaginative and Innovative Research Ideas and Concepts with Potential Military and Dual-use Applicability"

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

Submission of Proposals

DARPA's charter is to help maintain US technological superiority over, and to prevent technological surprise by, its potential adversaries. Thus, the DARPA goal is to pursue as many highly imaginative and innovative research ideas and concepts with potential military and dual-use applicability as the budget and other factors will allow.

DARPA has identified technical topics to which small businesses may respond in the first fiscal year (FY) 2003 solicitation (FY 2003.1). Please note that these topics are UNCLASSIFIED and only UNCLASSIFIED proposals will be entertained. Although the topics are unclassified, the subject matter may be considered to be a "critical technology." If you plan to employ NON-US citizens in the performance of a DARPA SBIR contract, please inform the Contracting Officer who is negotiating your contract. These are the only topics for which proposals will be accepted at this time. A list of the topics currently eligible for proposal submission is included followed by full topic descriptions. The topics originated from DARPA technical program managers and are directly linked to their core research and development programs.

Coversheet and Company Commercialization Report must be entered into the DoD electronic database in order for the proposal to be eligible for evaluation. Please note that **1 original and 4 copies** of each proposal must be mailed or hand-carried. DARPA will **not** accept proposal submissions by facsimile (fax). A checklist has been prepared to assist small business activities in responding to DARPA topics. Please use this checklist prior to mailing or hand-carrying your proposal(s) to DARPA. Do not include the checklist with your proposal.

DARPA Phase I awards will be Firm Fixed Price contracts.

Phase I proposals **shall not exceed $99,000,** and may range from 6 to 8 months in duration. Phase I contracts can ONLY be extended if the DARPA Technical Point of Contact wants to "gap" fund the effort to keep a company working while a Phase II is being generated.

DARPA Phase II proposals must be invited by the respective Phase I DARPA Program Manager (with the exception of Fast Track Phase II proposals – see Section 4.5 of this solicitation). DARPA Phase II proposals must be structured as follows: the first 10-12 months (base effort) should be approximately $375,000; the second 10-12 months of incremental funding should also be approximately $375,000. The entire Phase II effort should generally not exceed $750,000.

It is expected that a majority of the Phase II contracts will be Cost Plus Fixed Fee. However, DARPA may choose to award a Firm Fixed Price Contract or an Other Transaction, on a case-by-case basis.

Prior to receiving a contract award, the small business **MUST** be registered in the Central Contractor Registration (CCR) Program. You may obtain registration information by calling 1-888-227-2423 or Internet: http://www.ccr.gov.

The responsibility for implementing DARPA's SBIR Program rests in the Contracts Management Office. The DARPA SBIR Program Manager is Ms. Connie Jacobs. DARPA invites the small business community to send proposals directly to DARPA at the following address:

DARPA/CMO/SBIR
Attention: Ms. Connie Jacobs
3701 North Fairfax Drive
Arlington, VA 22203-1714
(703) 526-4170
Home Page http://www.darpa.mil